ASTROBIOLOGY PROGRAM

of the

University of Washington

Self-study Document

September 2005

Prepared for

the Graduate School's 5-year Review of the Astrobiology Certificate

and for

the College of Arts & Science's 5-year Review of a UIF grant to Astrobiology

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Executive Summary

Astrobiology ("AB") deals with life in a cosmic context, and is only a decade old as a field of study. Our central research theme is to understand (a) the origin, evolution, and distribution of life on Earth, and (b) the conditions on other potentially habitable planets, so as to inform where and how we should search for fossil or extant life on other worlds.

We are a graduate-only program that has developed new core courses, seminars, field workshops, and research rotations required for our Certificate in Astrobiology, which accompanies a student's PhD. Our AB Program has evolved from an academic experiment into the international educational leader of an emerging scientific discipline. Each student is firmly rooted in a home department — and gets the PhD there — but also spends considerable time becoming familiar with the broad range of science needed in AB.

<u>Funding history</u>. In 1998, thirteen UW faculty (from nine departments) received a 5-year $2.2M NSF IGERT (Interdisciplinary Graduate Education and Research Training) grant for AB (PI: Prof. James Staley of Microbiology). This allowed us to establish our AB graduate program and Certificate, the first formal AB program in the world. In 2000, largely on the strength of our initial progress and success, we received an internal UW grant (a University Initiatives Fund (UIF) sponsored by the College of Arts & Sciences; PI Prof. Woodruff Sullivan of Astronomy) to set up the Center for Astrobiology and Early Evolution, which is an "on-paper" center under whose rubric UW astrobiology activities are coordinated. In 2001 we used those funds to hire two new faculty specifically for the AB Program. In 2001 we received a 5-yr, $5.0M NASA grant (PI is Prof. Peter Ward of Biology) for AB research on "Habitable Planets and Evolution of Biological Complexity." This research award, which has been a vital complement to the IGERT grant, was based in part on our success in establishing a first-rate, nationally recognized AB graduate program. In Spring 2005 we were awarded a 5-year $3.2M renewal of the IGERT (PI: Sullivan).

Today in 2005 the AB Program has 28 participating faculty hailing from 12 departments. The 5 key departments in terms of active faculty and student participation are Aeronautics & Astronautics, Astronomy, Earth and Space Sciences, Microbiology, and Oceanography (which still involves us with 4 Deans!). Our strength lies in the quality of our people, which include three members of the National Academy of Sciences (Brownlee, Deming and Felsenstein). We currently have 19 regular AB graduate students (in 6 departments), 4 affiliate students, and 6 associated post-docs. Individual students have averaged 2 years on IGERT funds. To date we have awarded 4 AB Certificates and henceforth should average about 3 per year. We have attracted excellent students to the Program and the fraction of women and other underrepresented minorities is better or comparable to that of our consituent departments, but we have plans to greatly improve this record, especially via an alliance with a consortium of Historically Black Colleges and Universities interested in AB.

Past successes. AB's success at breaching disciplinary and administrative barriers at UW has encouraged others and helped ease their path. AB faculty are changing departmental attitudes towards the value of (1) "extreme" multi-disciplinarity, and (2) new approaches to education and administration. Our 19 students have been extremely successful in producing scientific papers (59 total), oral presentations at meetings (22), and posters (62). Several students have produced important papers in astrobiology. The four students who to date have received an AB Certificate have secured excellent first jobs and they took no longer to earn their degrees – a mean of 4.9 years. Innovative cross-disciplinary research has been spawned between both students and faculty.

We have an active K-12 outreach program called Project AstroBio, which sponsors 15 partnerships between scientists and Puget Sound teachers. We sponsor 2-3 public lectures each year and many AB faculty write books and articles for the public. We also have an active program of assessment conducted by the Graduate School's Center for Innovation and Research in Graduate Education (CIRGE).

Our primary areas of concern are related to: funding our students after the current IGERT grant expires in 2010-11; finding younger faculty to participate in the Program and succeed the current leadership; and finding more ways to encourage the cross-disciplinarity at the heart of our Program.

We have many further educational initiatives in process or planned. They involve two new AB graduate courses emphasizing experimentation and engineering skills; offering more opportunities for our students to improve their science writing skills; collaborating further with astrobiology groups at other US universities and in Germany; changing from a Certificate to a Joint Degree in "Department X and Astrobiology"; and designing a new AB course for upper-level science majors.

We also plan within a year to launch a campaign to locate foundation and individual philanthropic support for ten continual graduate fellowships in AB; this would require ~$250K/yr or an endowment of ~$5M.

We demonstrate in this document that the UW Astrobiology Program, although just starting its seventh year, has had significant successes and is transforming its graduate students, its faculty participants, its constituent departments and colleges, and the research field as a whole. We have accomplished in every way what we set out to do: to establish an innovative graduate program that is a world leader in an intellectually remarkable new field. This has happened because of hard work on the part of all concerned (including the students!), scientific acumen, significant support from UW administrators and outside agencies who placed their faith in us, and good timing.

In order to further the stated missions of the UW with regard to teaching, research, and public service, as well as to act in accord with the President's and Provost's strong support of interdisciplinarity, we submit that the UW could do no better than invest further in the Astrobiology Program. The Program is widely supported on campus ($190K/yr from many different UW units for the renewal 5-yr IGERT grant, summarized in Table 3 on p. 23) and is primed to go from strength to strength. To maintain our leadership in teaching and research in astrobiology, we request:

- an immediate faculty slot (start 2006) to replace the vacant AB position
- a third AB faculty slot in 2008
- matching money to stimulate major private donations
- a permanent staff position for the AB Program Coordinator (start 2010)
- two TA quarters per year for ASTBIO 115
- 50% support for one AB post-doc for five years

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1. Overview of the UW Astrobiology Program

[http://depts.washington.edu/astrobio]

1.1 Research focus

Astrobiology ("AB") deals with life in a cosmic context, and is only a decade old as a field of study. Its birth was catalyzed by the discovery of planets circling other stars, microbial life here on Earth living in extremes of temperature, pressure and chemistry, evidence for liquid water elsewhere in the solar system, and studies of the earliest history of life on Earth. Our central research theme is to understand (a) the origin, evolution, and distribution of life on Earth, and (b) the conditions on other potentially habitable planets, so as to inform where and how we should search for fossil or extant life on other worlds. Life exists on Earth under an amazingly wide range of conditions that may well exist on other planetary bodies, e.g., Mars or Jupiter's moon Europa. But whether or not any extraterrestrial life is ever found, astrobiology topics are of fundamental scientific value. The field continues to excite scientists and the public alike with, for example, recent discoveries of (a) compelling geological evidence from NASA's Mars Rovers for shallow seas of liquid water on the surface of Mars in its past, providing a possible habitat for life, (b) planets with masses of only ~15 times that of Earth circling other stars, suggesting that Earth-like planets may soon be detectable, and (c) cultivation of microbes at record high and low temperatures.

1.2 Graduate program

We are a graduate-only program that has developed new core courses, seminars, field workshops, and research rotations required for our Certificate in Astrobiology, which accompanies a student's PhD. In response to many studies urging changes in the traditional PhD experience, we directly address their recommendations such as multidisciplinary mentoring, broader intellectual exposure for students, improved faculty/student rapport, and training in teamwork and in communications skills. We produce top-quality students – for example, our students won first prize in 2002 and second prize in 2004 for the best student posters (out of ~ 50) at NASA Astrobiology conferences; three other students have also won prizes for posters elsewhere. Our senior students are now presenting their work at national and international conferences and publishing major papers (see Table 1).[1]

Astrobiologists must be thoroughly conversant with many disciplines, and expert in one or more. They must be able to do complex, multi-faceted science, and then explain it to audiences (both scientific and lay) who are unfamiliar with most of the underlying details. Producing such scientists under today's typically restrictive, department-dominated academic structure is difficuly, but we have striven to breach the walls separating disciplines.

Our AB Program has evolved from an academic experiment into the international educational leader of an emerging scientific discipline. Other universities (such as Penn State, Colorado, Arizona, Arizona State) look to our AB program as a model. Staley (2003), which describes our program and its philosophy, is attached as Addendum A. We have developed and implemented an interdisciplinary curriculum with unique features that bond together students and faculty from disparate departments. Each AB student has deep expertise in one field, plus sufficient knowledge in other areas to foster interdisciplinary research, especially between biological and physical sciences (see Secs. 4.3 & 4.4). The Program integrates research and education to create a new community of scholars and investigators -- the first PhD astrobiologists, those who will lead this emerging field. They are experts in their home discipline, as well as astrobiologists -- imbued with an interdisciplinarity that is highly unusual and sorely needed in both today's scientific community and in society at large.

So that our students not become "academic orphans," we have *not* created a new PhD (although in Sec. 10 we discuss our plans to change to a joint degree). Each student is firmly rooted in a home department — and gets the PhD there — but also spends considerable time becoming familiar with the broad range of science

[1] To showcase the productivity of the students in the AB program, citations marked "**" in this document or in the references list have one of our students as first author, while those with a single asterisk have a student as a junior author.

needed in AB (see Sec. 2). We expect our students' unique AB credentials to serve them well as researchers in academia, government labs or industry; as educators in academia (research universities and liberal arts colleges); as savvy administrators of increasingly interdisciplinary programs; and as science writers or journalists.

Our Program requires highly motivated students: they expend ~25% more total effort than their non-AB peers (without extending the time to degree; see Table 2). Our courses and seminars differ from the usual because of the diversity of student backgrounds and range of topics. They are not "dumbed down" versions of "proper" graduate-level courses, but rather new constructs — intense, high-level, and very challenging for both students and faculty. Drawing on the AB faculty's experience with two existing interdisciplinary courses (Geophys/Atm Sci 508 on "Biogeochemical Cycles" and Ocean 535 on "Biological Oceanography for Physical Scientists"), instructors have been able to maintain a fast pace and introduce only essential background and terminology, without sacrificing understanding of core principles and concepts.

In addition, every winter quarter, faculty and students jointly tackle via a student-driven seminaran important AB topic such as "planetary atmospheres," "the origin of life," or "instrumentation for remote life detection." Students also have a required research rotation (one preparatory quarter, one quarter in lab) – examples have included a microbiologist measuring spectra of stars, a biologist working on a new oceanographic instrument, and an astronomer studying microbial activity at different temperatures. Finally, faculty and students also annually take a 4-day field workshop designed to engage all in hands-on activities –examples are given in the next section.

1.3 Our history

In 1998, thirteen UW faculty (from nine departments) received a 5-year $2.2M NSF IGERT (Interdisciplinary Graduate Education and Research Training) grant for AB (PI: Prof. James Staley of Microbiology). This allowed us to establish our AB graduate program and Certificate, the first formal AB program in the world. Our first cohort of graduate students entered in 1999 and our first Certificate was earned with a PhD awarded in 2003. Our first IGERT award (also the UW's first) was critical to us in two ways: support for students, and freedom to try new approaches. The grant supported 48 student-years of IGERT research fellowships; student research and travel; a program coordinator; seminars and workshops; faculty release time for course development; and establishment of a new research facility (an Extremophile Lab for determining the extreme physical conditions under which microbes can survive or be active;Research Area #4 in Addendum B).

In 2000, largely on the strength of our initial progress and success, we received an internal UW grant (a University Initiatives Fund (UIF) sponsored by the College of Arts & Sciences; PI Prof. Woodruff Sullivan of Astronomy) to set up the Center for Astrobiology and Early Evolution, which is an "on-paper" center under whose rubric UW astrobiology activities are coordinated. In 2001 we used those funds to hire two new faculty specifically for the AB Program (Prof. Roger Buick of Earth & Space Sciences, who studies micro-paleontology and geochemical biomarkers in the oldest geological formations, and Prof. David Catling of Atmospheric Sciences, who models the history of planetary atmospheres and develops instruments for missions to Mars). In March 2005 we lost Catling to Bristol University (UK), which gave him a remarkable offer in terms of salary and the opportunity to set up an astrobiology program in his homeland. UW departments have also made several other supportive faculty hires, e.g., in Astronomy (Prof. Tom Quinn) and Microbiology/Civil and Environmental Engineering (Prof. David Stahl).

Renewal of IGERT grants is even more competitive than the initial grants; we were not successful in our first renewal attempt in 2003, but nevertheless carried on through prudent spending and no-cost extensions until our successful 5-year $3.2M renewal of Spring 2005 (PI: Sullivan) (only about one-quarter of existing IGERTs that were invited to propose eventually were funded). This "renewal group" involves 18 faculty from 9 departments.

In 2001 we received a 5-yr, $5.0M NASA grant (PI is Prof. Peter Ward of Biology) for AB research on "Habitable Planets and Evolution of Biological Complexity." The award was based in part on our success in establishing a first-rate, nationally recognized AB graduate program. This research funding is a vital complement to the IGERT grant. The NASA funding, for example, allows us to support talented foreign students (not allowed by NSF's regulations) and postdocs. It permits a vigorous research effort to accompany our graduate education program, and makes us one of the 15 members of NASA's Astrobiology Institute (NAI) -- the world's foremost institution for AB research. Within NASA we are acknowledged as *the* experts on AB graduate education; in fact, we are building the UW AB philosophy into the design of various training workshops, sessions at meetings, and funding opportunities that NASA itself sponsors. This autumn we are applying for a five-year renewal of this NASA research funding, to begin in July 2006.

Today in 2005 the AB Program has 28 participating faculty, of which the 19 most active are listed below. Our total faculty hail from 12 departments (Aeronautics & Astronautics, Astronomy, Atmospheric Sciences, Biology, Civil and Environmental Engr., Earth and Space Sciences, Education, Electrical Engr., Genomic Sciences, History [of Science], Microbiology, and Oceanography) and 4 Colleges or Schools (Arts & Sciences, Ocean & Fishery Sciences, Medicine, and Engineering). The 5 key departments in terms of active faculty and student participation, however, are Aeronautics & Astronautics, Astronomy, Earth and Space Sciences, Microbiology, and Oceanography (which still involves us with 4 Deans!). As with any organization, our strength lies in the quality of our people; the CV's of our faculty in Appendix G attest to their excellence, including three members of the National Academy of Sciences (Brownlee, Deming and Felsenstein).

We have 19 regular AB graduate students (in 6 departments), 4 affiliate students, and 6 associated post-docs. Individual students have averaged 2 years on IGERT funds, usually during their formative first three years. To date we have awarded 4 AB Certificates and henceforth should average about 3 per year. Testimony addressing the quality of the students is in Secs. 4.3 and 4.7.

Nota Bene 1. In reading this document remember that we are basically a small (although we think excellent) program compared to even small academic departments. We do have one major research grant from NASA and a major educational grant from NSF, but most of what gets done by faculty with respect to the AB Program is voluntary. We have a staff of 2.3 FTE (0.5 of which is via UW matching funds) and rely heavily on our constituent departments for recruiting and advising of graduate students.

Nota Bene 2. The present review of our Program is simultaneously for the benefit of the Graduate School, which reviews all new Certificate Programs after five years; and for the College of Arts & Sciences, which after five years is also reviewing its College UIF funding to Astrobiology.

Most Active Faculty in the Astrobiology Program

Woodruff T. Sullivan, III (Astronomy)
    Chair: Astrobiology Steering Group (members marked with *)
John A. Baross (Oceanography)
Michael Brown (Earth & Space Sciences)
Donald E. Brownlee (Astronomy)
Adam Bruckner (Aeronautics & Astronautics)
*Roger Buick (Earth & Space Sciences)
*Jody W. Deming (Oceanography)
Joe Felsenstein (Genomic Sciences)
Richard H. Gammon (Oceanography)
Deborah S. Kelley (Oceanography)
John A. Leigh (Microbiology)
Alexander V. Mamishev (Electrical Eng.)
Kristi Morgansen (Aeronautics & Astronautics)

Maresi Nerad (Education)
*David A. Stahl (Microbiology/Civil & Env Eng)
*James T. Staley (Microbiology)
Thomas R. Quinn (Astronomy)
*Peter D. Ward (Biology/Earth & Space Sciences)
Stephen G. Warren (Atmospheric Sciences/Earth & Space Sciences)

2. Requirements for the Graduate Certificate in Astrobiology

The AB curriculum includes new graduate-level core courses, field workshops, a research rotation, and a seminar series, all required *in addition to* each student's departmental requirements.

Core courses.

ASTBIO 501 - Astrobiology Disciplines. This provides an introduction and concise background to core concepts and essential terminology of the relevant disciplines contributing to AB. Each week a faculty expert in one area is teamed with an incoming student also knowledgeable in that area. If a week's lecture topic is, for example, paleontology, a faculty paleontologist works closely with a graduate student (who has studied some paleontology) to prepare two lectures, one by the faculty member, the other by the student. The pair also lead a lab exercise or a discussion of a recent paper. This format has worked very well, greatly enhancing faculty-student interactions.

ASTBIO 502 - Astrobiology Topics. This consists of one or more parts, coordinated by an AB faculty member and each led by an AB faculty expert. One part ties in with the Annual Workshop topic. A recent example included topics of: history of the Earth's atmosphere (Prof. Richard Gammon of Oceanography/Chemistry), evidence for early life (Prof. John Baross of Oceanography), and mass extinctions and consequences of impacts of extraterrestrial objects (Prof. Ward of Biology). There was an accompanying workshop at the Friday Harbor Laboratory centered on fieldwork in paleontology and marine biology. The topic in Autumn 2005 is "Life on Mars?".

A third interdisciplinary course, chosen from a list of existing suitable courses, and also from specially devised AB-cognate departmental courses, is also required.

Field workshops. The annual 3-day workshop has become an excellent format for informal off-campus interaction and instruction of both students and faculty. The first was at Pacific NW National Labs (PNNL) in Richland, Wash. Students and faculty spent three days in the field, learning about PNNL research through discussions, demonstrations, geology field trips, and hands-on microbiological research. Regardless of research field, each participant sampled underground microbiota in deep wells and studied them through the fall term. The second workshop was at NASA Ames: we met with astrochemists studying space organic chemistry, the Kepler Mission team who will be searching for Earth-sized planets circling other stars (launch in 2008), microbiologists studying microbial mats, planetary scientists, and others. In one session students and faculty identified possible Martian landing sites using computer mapping databases. Later workshops have been at the UW's Friday Harbor Marine Biology Lab (paleontology of the late Cretaceous, plus examination of invertebrates gathered off the ocean floor to learn about the Cambrian Explosion), and in Eastern Washington focusing on the evidence for catastrophic floods that produced the Washington "Channeled Scabland" terrain (similar to some ancient landscapes on Mars). In March 2005 we had our first joint workshop with another university when we had an astronomy-themed workshop hosted by the University of Arizona at Kitt Peak National Observatory; in turn we will be hosting them in October 2005 at a workshop at Friday Harbor.

Research rotations. After a preparatory reading quarter, every AB student must spend at least one quarter working in a lab outside his/her area of expertise. Three examples: (1) a geology student studying desert "rock varnish" rotated through a microbiology lab, which led to a co-authored paper on microbes associated with varnish formation (**Perry *et al.* 2003); (2) a biology student participated in the engineering development of a new oceanographic sampling device (which also led to a co-authored paper, *Phillips *et al.* 2003); and (3) a microbiology student measured spectra of stars with orbiting planets to analyze their chemical compositions (*Laws *et al.* 2003).

The AB Seminar series. During fall and spring we invite outside speakers who give jargon-free introductions to their topic for part of their lectures, to enable those in other fields to understand the research results that follow. These seminars, over a broad range of topics, have been well attended. During winter quarter we hold an "in-house" seminar series that pairs faculty and students across disciplines to give presentations on a particular AB topic. For example, during the topic of "Planetary Atmospheres" a biology student lectured on the Martian atmosphere, after working closely with an atmospheric scientist. The winter series fosters close student interaction with faculty from other fields and provides a valuable learning and teaching experience.

Thesis. Each student's PhD thesis committee must include two AB faculty members from outside the home department, and the thesis topic must be relevant to astrobiology.

3. Research Themes

Five major research areas, as presented to NSF in our IGERT proposal, underlie our Program's educational efforts.[2] Each area addresses parts of the general theme, involves several AB faculty members, and is supported by significant outside research funding (NSF, NIH, NOAA, and especially NASA, as mentioned above). Although presented here as separate topics, they are actually closely intertwined and mutually supportive. Research Area #1 is a new one in Engineering, and involves designing, building and remotely controlling exploring devices: if we are to look for life, especially in extreme environments, we need effective search tools. Areas #2 and #3 explore questions of planetary habitability: where shall we send the devices we build? Area #2 examines the formation and subsequent changes in candidate planetary sites for life, while Area #3 studies how planetary catastrophes may actually be a necessary driver in the development of diverse life on any habitable planet. Area #4 studies physiological and environmental limits to life: it is essentially a finer-scale look at habitability, and gives clues about what to look for in terms of life's chemistry (thus influencing which detection devices to build in Area #1). Finally, Area #5 considers how and when complex life might evolve from simple forms, which influences both where to look and what to look for.

Addendum B has details of each of these major areas, with literature citations and many examples of how our graduate students are involved. Many other smaller astrobiology research projects exist, but these five areas cover a major portion of the effort.

4. Past Successes of the Program

4.1 Shifts in academic culture

AB's success at breaching disciplinary and administrative barriers at UW has encouraged others and helped ease their path. AB faculty are changing departmental attitudes towards the value of (1) "extreme" multi-disciplinarity, and (2) new approaches to education and administration. For example, the School of Oceanography has recently revamped its graduate requirements to encourage and support AB students (by lightening their oceanography-only requirements in favor of AB coursework). It is no longer startling that, for example, UW microbiologists and astrono-

[2] IGERT monies fund neither faculty salaries nor research - they support the graduate students and their education. A requirement for an IGERT is that the faculty proposing it have an integrated research program upon which to float the educational experiment.

mers talk to (and understand!) one another, or that a geologist collaborates with an expert on the Martian atmosphere. AB faculty have effected this cultural change through success begetting success: by attracting and training first-rate graduate students, by garnering attention from other students and faculty, as well as from national and international colleagues, and by producing quality research. Our students, who are quite vocal about the program's unique benefits, are AB's best advertising to their peers.

Innovation in interdisciplinary graduate education is taking hold on the UW campus. We have helped build mechanisms and the climate for successfully instituting cross-disciplinary efforts. Four other IGERT awards to UW have since followed ours; a recent example of a *non*-IGERT program that sought our advice as it began is the interdisciplinary Program on Climate Change. Beyond UW, dissemination of our program's practices informally and through talks at meetings has definitely influenced several other universities (Penn State, Arizona State, U. Arizona, etc.) as well as the NASA Astrobiology Institute.

4.2 Helping to invent a new field of science and new style of education

Our AB program was funded in NSF's first cohort of IGERTs (1998), when the field of astrobiology was only 2-3 years old. Astrobiology was a completely novel topic for graduate education, so the program began *de novo*. Since there were no AB textbooks or journals, we developed our curriculum from scratch. This was especially challenging because AB touches upon many different subjects, taught within a great range of departments. We matured quickly and today have an effective, world-recognized graduate AB Program. Meanwhile, the field has developed two journals, other research and educational programs, and significantly greater funding for research, especially through NASA.

4.3 Successful students

Our efforts have led students to innovative interdisciplinary work and thinking. Our students are excited by the exposure they receive to such a variety of disciplines, and to the fundamental nature of the questions raised by astrobiology, many of which form at the interface between disciplines and would not otherwise arise. Several students have commented that, in comparison to AB programs that have recently formed elsewhere, ours has far more coherence and richness: as one AB/Astronomy student put it: "At UW the AB Program offers *an interdisciplinary culture*, not just interdisciplinary research." An AB/Microbiology student who had worked in industry said that she had been searching for eight years for such a program that melded the physical and biological sciences in the search for life. Another

AB/Astronomy student related that the program had not just taught him some new things, but had fundamentally changed how he thought about his core Astronomy courses— he is now constantly looking for the nexus between the cosmos and the phenomenon of life. Finally, students have realized how their different “AB way” of learning (and experience with helping to develop curriculum) has already profoundly affected their own teaching (as sometime TAs).

As Table 1 (following page) shows, our 19 students have been extremely successful in producing scientific papers (59 total), oral presentations at meetings (22), and posters (62). The average per student of 2.6 “achievements”/yr is above the value of 2.2 for all comparable NSF-funded programs (Brizius & Luckey 2000). (Note that our tally of achievements does *not* include prestigious non-IGERT fellowships, travel grants, and other recognitions that many of our students have received.) Our four students who to date have completed the PhD and received an AB Certificate have secured excellent first jobs (see Sec. 4.7); and they took no longer to earn their degrees – a mean of 4.9 years (compared to the NSF GRT value of 5.5 years).

Table 1

Astrobiology Graduate Student Research Achievements

Yrs	AB IGERT Student	PUBLICATIONS Submitted	In press	Published	CONFERENCES Posters	Talks	Proc.	Total	# per year
4	Armstrong (Astr)	1	2	4	3		6	16	**4.0**
2	Brazelton (Ocean)	1			1			2	**1.0**
2	Claire (Astr)	1			7	1		9	**4.5**
2	Collins (Ocean)	1	1		4			6	**3.0**
4	Dodsworth (Microbiol)	1		2	1	1		5	**1.3**
3	Harnmeijer (E &Sp.Sci.)			1	5			6	**2.0**
5	Huber (Ocean)	1	2		2	1	1	7	**1.4**
4	Junge (Ocean)	1		9	3			13	**3.3**
1	Kaib (Astr)			1			2	3	**3.0**
1	Kirkpatrick (Ocean)				1			1	**1.0**
4	Kristall (Ocean)			1	3			4	**1.0**
4	Perry (E &Sp.Sci.)	1	2	4	10	9		26	**6.5**
3	Pinel (Microbiol)							0	**0.0**
4	Raymond (Astr)	3	2	2	1	4		12	**3.0**
1	Sauter (Microbiol)				1			1	**1.0**
5	Schrenk (Ocean)	1		4	14	3		22	**4.4**
3	Vance (E &Sp.Sci.)	2			3	3	1	9	**3.0**
5	Wells (Ocean)	4	1	3	3			11	**2.2**
1	Williford (ESS/Biology)							0	**0.0**
	Total	18	10	31	62	22	10	153	**2.6**

Our goal is to produce intellectual breakthroughs that originate with the students themselves, not as offshoots of established faculty research programs. For example, AB/Astronomy student John Armstrong and AB/Biological Oceanography student Llyd Wells were lead authors (working with an AB postdoc) in writing two papers that were published in the premier planetary journal, *Icarus*. They propose that the Moon may well be "Earth's attic," in that the Moon's surface soil likely contains particles and rocks with signatures of life that were ejected (by impacts) from Earth to the Moon over the past 4.6 billion years (**Armstrong *et al.* 2002).

These signatures (and perhaps even fossils) would be well preserved because on the Moon they have not been exposed to weathering and tectonic processes, and may contain important clues about Earth's early history. In a second paper, they point out that microbial life may have survived huge sterilizing impacts early in Earth's history by being ejected off the planet and then returning after conditions were again clement (**Wells *et al.* 2002). These AB student papers are influencing NASA's scientific planning for missions to the Moon**.** In fact Armstrong obtained his PhD in 2003 and has already served on a key NASA study team regarding the rationale for returning spacecraft to the Moon. In another example of novel and exciting interdisciplinary research originating with our students, AB/Earth & Space Sciences student Randy Perry is lead author on an innovative study of the evolutionary principles that may have applied within the pre-life biochemical "soup" and a later "transition zone" when chemical cycles become more complex and lifelike. (**Perry & Kolb 2004).

Another technique we have employed is to directly involve our students in the shaping of our major research proposals. In Winter and Spring 2005 students actively critiqued faculty presentations of possible research themes for our current NASA proposal (for five-year renewal in NAI). This philosophy is culminating now with the novel approach of a sub-project (to be included in the proposal) that is wholly student generated and written and identified as such. As this is being written in late September 2005, we have 3 excellent student "preproposals" from which we must make a difficult choice!

Several of our AB grad students are coauthors of chapters in an in-press graduate textbook for AB (see below); in addition, one chapter (**Wells *et al.* 2006) was written solely by IGERT graduate students on the topic of the nature of Astrobiology , as well as its future. A sample:

> In the end, astrobiology may bring us back to the integrative style of someone like Johannes Kepler four hundred years ago. He was not content merely to bequeath the world a detailed quantitative theory of orbital motion, but instead wrote a great synthesis of the Universe. He understood it as a musical masterpiece, an orchestra of resonating orbits and celestial movements. Why are we scientists? - why are we teachers? - why are we curious? - if not to ask the grand questions that we cannot answer. Astrobiology is an opportunity for science to reincorporate some of the intemperance and ambition of earlier, more comprehensive approaches. No guarantee exists that these types of approaches will necessarily lead to fundamental insights, but if the equivalent of Kepler's famous Laws should emerge from the next great synthesis, this grand new enterprise of astrobiology would have proved its worth.

4.4 Cross-disciplinary collaborations among the AB faculty

Examples of cross-disciplinary collaborations among the AB faculty include: (1) a paleontologist plus two astronomers invented the concept of the "Galactic Habitable Zone," i.e., the portion of the Milky Way wherein chemical and physical conditions are optimum for life (Gonzalez *et al*. 2001); (2) a paleontologist and an astronomer published the two popular books *Rare Earth: Why Complex Life is Uncommon in the Universe* (Ward & Brownlee 2000) and *The Life and Death of Planet Earth: How the New Science of Astrobiology Charts the Ultimate Fate of our World* (Ward & Brownlee 2003); (3) catalyzed by jointly advising an AB student, a biological oceanographer (Deming) and atmospheric scientist (Warren) are collaborating on the availability of liquid water in deeply frozen environments; and (4) an atmospheric scientist (Catling) and biogeochemist (Buick) studied the carbon cycle and its variations at the time of the great Permian/Triassic mass extinction (*Buick *et al.* 2004). This project (like the others) could not have been undertaken without the combined expertise brought together by our program, especially through the person of an AB/Astronomy grad student.

UW's AB faculty have also conceived, edited, and largely written (about 40% of the chapters) the first graduate-level AB textbook, *Planets and Life: The Emerging Field of Astrobiology* (eds.: astronomer Sullivan and microbiologist Baross: Cambridge U. Press, 2006). The chapter authors are drawn mainly from the invited speakers at a very successful conference on AB hosted by us. All 27 chapters, covering the gamut of AB, are designed to be understandable to all science graduate students who want to learn the basics, no matter what their background. Our AB pedagogical philosophy suffuses this book – its publication will efficiently disseminate our conviction that graduate training *is* possible and needed across traditional disciplines.

4.5 Post-docs

Our first IGERT grant 50%-supported two post-docs (one woman, one man) for two years. These post-docs were very important for mentoring, for helping to develop and execute our curriculum, for contributions to workshops and seminars, and for generating research ideas. Inculcated with our IGERT teaching and training practices, they are now in tenure-track faculty positions at San Diego State Univ. and Santa Clara Univ. We are now funded for 50% of two post-doc positions for a full five years, and look forward to soon filling these slots with their first tenants.

4.6 Outreach to K-12, the public, and the profession

Our AB Program has had widespread impacts far beyond academia. AB subsumes all the sciences and asks basic questions that have always fascinated humans. It is an ideal vehicle for bringing science to the general public, to the K-12 classroom, and to non-science majors in universities. The UW AB Program reaches out through Project AstroBio (with Sullivan as Director, supported by NASA and private funds) to provide year-long partnerships between scientists and grades 3-12 teachers via two-day training workshops, classroom resources, and other programs and materials. Today, there are ~50 active partnerships in the greater Seattle region. Eight AB grad students, post-docs, and faculty have participated as partners with teachers (and one of our MS-level graduates is dedicating her career to high school science teaching, as mentioned in Sec. 5). We work closely with NASA's Washington State Space Grant, housed here on campus (Director is Janice DeCosmo) and, if NASA funding is secured for another five years,we will further improve this "K-12 Education/Public Outreach" component.

In addition to popular articles and books, many of us frequently appear on radio shows, in newspaper articles, and in video (PBS Nova, Discovery Channel). The AB Program sponsors two public lectures annually on AB topics – these typically draw crowds of 200-500. In early 2003 we also sponsored (and six of us spoke at) a very well received special session at the American Astronomical Society on "The Biology of Astrobiology for Astronomers." After proposing another idea to the Vatican (Jesuit) Observatory in Italy, in the summer of 2005 Baross and Sullivan were part of the faculty at a four-week Summer School on Astrobiology (for seniors and beginning grad students from around the world). Twenty-five excellent students from around the world were exposed to a wide variety of astrobiology topics, and several of the best now plan to apply for graduate school at the UW.

4.7 Careers for our Graduates

Our graduates have a choice of many routes for their careers. Many of our senior students (4th year and beyond) have already received inquiries about their availability for post-doctoral positions; as a result of their unique training and important publications, they are in high academic demand even before completing the PhD. To date we have four AB graduates and each one has gone on to an excellent first job. John Armstrong (Astronomy) is an assistant professor at Weber State Univ. (Utah) and halftime working on Astrobiology for NASA's JPL. Randy Perry (Earth & Space Sciences) continues to collaborate with many researchers at top labs on a variety of astrobiological topics (he was a non-traditional student – aged 50, independently wealthy). Julie Huber (Oceanography) now does molecular astrobiology research, supported by a prestigious NRC/NAI post-doc at the Marine Biology Laboratory in Woods Hole, Mass. Finally, Matt Schrenk (Oceanography) has just started a similar NRC post-doc at the Carnegie Institution of Washington, working on extremophilic microorganisms living at ocean-floor hydrothermal vents.

Other indications suggest that a significant fraction of our graduates will be attracted to non-standard endeavors, either as important components of traditional careers in academic and research-oriented positions, or as careers in science writing and speaking to the public, teaching at all levels (from high school to graduate school), museum work, studying the relationships of science with history, philosophy, and technology, and science administration with a uniquely comprehensive scientific background. This variety we deem very positively: society needs PhD students who intimately understand science and aspire to other than the academic scene.

5. Recruitment & Diversity

5.1 The record to date for students

Table 2 below shows that 27% of our students have been women, compared to 37% for the NSF cohort referred to above (Brizius & Luckey 2000). We formerly had one African-American student (his story is told below), and now have two African-American women. Thus we now have 9% African-Americans in our program, a higher ratio than in *all* of our participating departments and comparable to the NSF cohort (11%), but a record we nonetheless intend to improve.

Our withdrawal rate (from the home department's PhD program) over the past five years has been 21% (Table 2), statistically identical to the 18% for the NSF cohort. Yet we consider two of our seven "withdrawals" to be in reality successes. David Allen, an African-American AB/Oceanography student always wanted to contribute to issues in global marine science and policy. Because of his IGERT-supported interdisciplinary education, broadened interactions, and international opportunities, he was able to achieve his goal after earning an MS, when he was offered a staff liaison position to NSF at the US Global Climate Research Program in Washington, DC. Another AB student, Diane Nielsen, also stopped at the MS level. Through the unique opportunities of our program, she came to believe in her abilities to contribute to the nation's scientific literacy. She is now a highly regarded science teacher at Mercer Island H.S., whose AB training has provided a marvelous background for her chosen career.

Selection of AB graduate students is overseen by an AB recruitment committee and done in parallel with recruitment by departments. Students are admitted to

AB and to their home departments and offered two-years of RA support – IGERT-funded if US citizens or, if foreign, NASA-funded or UW-match. The remainder of a student's support comes from research grants and TA positions (typically 0.5-1 year for each student).

Table 2

Recruitment & Retention History

UW Astrobiology IGERT Program Students: 1999-present

	Applicants	Accepted	Enrolled	Withdrawn	PhDs	Current
Total	216	52	33	7	3	23
Women	78	21	9	3	1	5
Minorities	15	5	3	1	0	2
Disabilities	0	0	0	0	0	0

	UW AB	**NSF GRT** (Brizius & Luckey 2000)
% Women	27%	37%
% Minorities	9%	11%
% Withdrawing	21%	18%

Mean time to PhD	4.9 yr	5.5 yr
Achievements/year	2.6	2.2

5.2 Plans to improve diversity

We want to improve our mentoring for *every* AB student, but are concentrating on two under-represented groups: (1) African-Americans, and (2) women. The general problems are (a) finding students, and then (b) keeping them in the program. Although we necessarily strongly rely on our constituent departments for much of our recruiting and mentoring, we nevertheless want to improve the environment for our AB students. For African-Americans, we have a strong collaboration with Tennessee State University, designed specifically to recruit and retain African-Americans (described in detail below). The McNair Program and a Western Name Exchange (of minority undergrads interested in grad school) also assist us in locating prospects. For women we will use UW's WISE program (Women in Science and Engineering) for outreach to women, recruiting, and developing mentoring programs.

5.2.1 African-Americans in AB

We plan to better use the considerable expertise of the Graduate School (in particular, the GO-MAP program), especially since this will be our new administrative home. We have also recently greatly strengthened our minority recruitment effort through collaboration with the new Minority Institutions Astrobiology Consortium (MIAC) of nine Historically Black Colleges and Universities (HBCUs) interested in AB research and education (Tennessee State Univ. (TSU), South Carolina State Univ. (SCSU), Hampton Univ., Bennett College, Texas Southern Univ., Benedict College, Houston Community College, Cheyney Univ., and North Carolina Central Univ.). In 2002, Prof. Sullivan participated in the “founding workshop” of MIAC in Maryland. MIAC is led by TSU Prof. T. Gary — he is now our paid consultant (one month/yr) to facilitate an active mutual exchange of students and faculty. TSU is a natural leader of MIAC – it has a fine publication record in AB (on extrasolar planets – e.g., Henry *et al.* 2000), and its new Institute for Understanding Biological Systems (directed by Gary) has NASA funding for research and educational outreach in AB and related fields. TSU is committing significant funding ($34K/yr) to forge a strong partnership with our program, e.g., paying for MIAC student stipends while at UW, and for other UW and TSU exchanges between our campuses. In turn, the Graduate School is supporting our tie with MIAC with one minority RAship per year and $5K/yr support towards a summer course aimed at minority undergrads (see below). Only through such long-term, concerted personnel interchange does effective recruitment happen.

HBCUs are a primary source of African-American students who later earn higher degrees in the sciences (Leggon & Pearson 1997). We plan concerted efforts to prepare undergraduates, to attract them into AB, and to mentor them in ways that will keep them progressing well towards the PhD. To further these ends, we are contributing $10K/yr towards a new position: a fulltime person shared with other IGERTs and NSF Centers on the UW Campus (an *ad hoc* UW committee headed by Prof. Al Kwiram, on which we sit, is now carrying out a search). Furthermore, AB faculty will regularly visit TSU and other MIAC institutions to lecture and advise on AB topics, to better understand the challenges and opportunities of educating future scientists at HBCUs, to make personal contact with faculty and undergraduates, and to foster interactions with NAI. The first exchange visit was Prof. Gary’s visit to UW (8/2004); further visits were in Nov. 2004 (Sullivan to TSU) and Feb. 2005 (Prof. Jody Deming of Oceanography to SCSU).

We expect a significant increase in African-American students in our Program; initial results have been extremely promising with the 2004 recruitment of two African-American women, one of whom came from TSU. We have also appointed Prof. Deming as Minority Recruitment Faculty Advisor. Mutually-funded exchanges between UW and MIAC will feature summer AB research jobs for MIAC undergrads and grad students, longer-term residencies at UW for TSU grad students, and extended visits to UW by MIAC faculty. Furthermore, a regular series of informal, two-way, "get to know the scientists and their science" sessions will be Webcast from UW to TSU over a broadband NASA system. Student attendance at TSU will be stimulated with free pizza and soft drinks. Another recruiting vehicle will be to invite one or two MIAC undergrads along on our annual AB field workshop.

Summer undergraduate AB short course. With TSU and MIAC and extensive support from the UW's GO-MAP program, we will develop and hold at UW week-long summer courses for undergrad students interested in AB. GO-MAP's Director, Dr Johnnella Butler, has developed similar courses in other fields, and will hold training and planning sessions for AB faculty on how to be most effective in this setting. This program will be open to all, but aimed especially at under-represented minorities.

Undergraduate Research Jobs and Graduate Student Residencies. We will provide summer research jobs for TSU and other MIAC undergraduate students, to encourage students to stay in science and eventually apply to the AB program (or other graduate programs). In addition, MS and PhD students from TSU and other MIAC members will come to UW for research-oriented visits and/or to take our AB courses and seminars.

5.2.2 Women in AB

In terms of participation by women, our record has been comparable to that in our various departments, but this nevertheless can be improved. As tabulated in Table 2, we have had 27% women students, compared to NSF's Graduate Research Traineeship Program average of 37% (Brizius & Luckey 2000). Recent stronger efforts (and recruiting more women to our faculty) have yielded results: our most recent seven-student cohort (2004) includes four women (of whom two are African-American). We will work with WISE to mentor them and to continue a solid recruiting record. We also strive to promote a culture of diversity through more women's visibility in teaching and research across our disciplines; for example, the fraction of women faculty on the renewal IGERT was 21%, compared to 5% for our first IGERT.

Future AB searches for faculty and post-docs will be very proactive, as we have been in the past, both in the make-up of the search committees and in considering women and minority candidates.

5.3 Mentoring

We plan stronger mentoring efforts to help us retain our recruited students. Our program already has both formal and informal mentoring, including structured pairing of students with faculty and with fellow students during our winter seminar format. We will expand this to include long-term pairings centered on research, training, and other affinities. We also plan to better learn the art of mentoring through having AB faculty take an intensive short-course in mentoring from Prof. Suzanne Brainard, Director of the Center for Workforce Development and Prof. of Women's Studies and Technical Communication.

In our present advising process, students are kept informed of the requirements of the AB Program and are actively involved in evaluations of their own progress. Students are initially assigned an ad-hoc committee of advisors. By the end of Year 1 most students have chosen their final advisor. Each student's progress is evaluated annually via a progress report and a student-advisor meeting after a discussion by the entire AB faculty. These evaluations are run in parallel with, and complementary to, those of the home departments.

With our renewal IGERT we are beginning to pair each new AB student with an advanced AB student or post-doc. Post-docs, situated in the hierarchy between grad students and faculty, are often ideal for mediating faculty-student relations.

Our AB students also currently benefit from informal peer mentoring and group support through a social "organization" (colloquially called UWAB) that they established early on.

6. Teaching

Courses specifically for the Astrobiology Program are few, but important. The only explicit teaching resources assigned to AB are one-third of the two faculty positions granted to us by the UIF (Buick and now-departed Catling) and one-sixth of Prof. Don Brownlee (Astronomy), which came about as part of a retention package about five years ago. Much of AB teaching, coordination of seminar series, workshops, etc. is volunteered by AB faculty on top of their regular departmental teaching duties. Evaluation of teaching is done through the usual survey and feedback forms.

Graduate. In alternate autumns we teach ASTBIO 501 and 502 (described in Sec. 2). Furthermore, in each two-year cycle we teach on average about one additional explicitly AB course, and 2-3 departmental courses with AB in mind (e.g., Buick's "Early Earth Evolution" or Gammon's "Biogeochemical Cycles"). Every quarter we also run a seminar at 2:30 on Tuesdays (this is AB's "sacred time" that fits into 90% of all schedules), whose format changes from quarter to quarter (Sec. 2). Example formats are potpourri of topics from outside speakers, single-theme quarters, internal speakers (mostly students) sharing their current research results and plans, tutorial topics presented by both faculty and students, etc.

Undergraduate. We also teach once per year the very successful ASTBIO 115 (also cross-listed as Biology 115, Oceanography 115, Astronomy 115, and ESS 115!), a 5-credit introduction to astrobiology for nonscience majors. This couse provides an excellent opportunity for some of our grad students to have a TA experience, although we have been limited by available UW funds as to how many sections we can offer (so far only 1 TA covering 50 students in two sections). This also limits how many of our grad students can have this excellent teaching experience. Over the years several AB faculty have also taught 300 or 400-level special topics courses on Astrobiology for science majors, but we have not yet instituted, say, ASTBIO 350 designed for science majors; this we plan to do (Sec. 10.1.5). We do *not* feel it appropriate to fashion an undergraduate major in Astrobiology, as it would be a mistake for an undergrad science student to become too spread out in their knowledge; rather, at that point in their career a student needs to become thoroughly grounded in one of the traditional sciences and study astrobiology only for further enrichment. We have considered the possibility of an undergraduate *minor*, but simply do not have the resources to run such a program. We also contribute to undergraduate studies through research jobs (averaging ~6 students/yr) that we support through NASA Space Grant and on an *ad hoc* basis.

7. Management & Budget

7.1 Management

For whatever reason the AB faculty, despite (because of?!) their disparate origins, get along well, are not "empire builders," and in general strive successfully to row together. Our present management structure centers on a Steering Group for the Center for Astrobiology and Early Evolution that coordinates all AB matters. Sullivan is current Chair and other current members are Deming, Ward, Staley, Buick, Stahl, and Billy Brazelton of Oceanography as (voting member) grad student representative. The Steering Group has operated now for six years in an enjoyable, collegial manner. It manages and coordinates recruitment, evaluation, faculty and staff issues, research programs, teaching of courses and seminars, other AB events, tracking of AB student progress, undergraduate courses and research jobs, public outreach, and relations with agencies. It also oversees our relationships with outside institutions such as the Minority Institutions Astrobiology Consortium (Sec. 5.2.1), NASA Ames and JPL, as well as our new international program with Germany (Sec. 10.1.4).

The renewal IGERT's administrative home is in the Graduate School, rather than one of our constituent departments. The Graduate School and AB recognized the need for a locus outside of departmental boundaries and administrative structures for pioneering multidisciplinary efforts like ours, and so took this step. We hope this will lead to closer ties to other IGERT and cross-departmental programs on campus. The Graduate School has been a national leader in fostering and studying interdisciplinary education, for example, with its project "Re-envisioning the PhD" (Nyquist & Woodford 2000). It is no accident that our IGERT has been followed by three others at UW (Nanotechnology, Urban Ecology, and Multinational Challenges to the Environment).

The Graduate School is also providing office space for our fulltime Coordinator (Nancy Quense), who is AB's key staff member for administration, budget, coordination of events, and secretarial duties. Other staff members are 0.6 FTE Nomi Odano, who solely administers the NASA grant, and Linda Khandro (varying from 0.5 to 1.0 FTE) who runs the NASA Education/Public Outreach program, centered on Project AstroBio (Sec. 4.6).

Social activities. It is vitally important that students in a new and nonstandard program form their own community - this is known to be one of the strongest types of mutual support towards remaining in a program. The "UWAB" student group has already been mentioned in Sec. 5. Another student group runs a weekly session (with pizza), to review recent journal articles. Faculty, post-docs, staff and students also hold a monthly social hour to get to know one another better, as well as foster exchange of ideas. We hope eventually to secure a dedicated AB meeting room for social and other get-togethers – microwave oven, sofas, computers, and room keys only for AB students, but do not yet have such an identified space. AB faculty believe strongly in the importance of this socializing, and have contributed about $2500/yr of personal funds towards social events.

7.2 Budget

The UW Astrobiology Program has these sources of support:

- IGERT program (NSF) (currently funded 2005-10)
- NASA Astrobiology Institute (2001-2006)
- Arts & Sciences UIF award (2000-)
- UW matching funds for NSF and NASA grants
- private donations

The annual **IGERT Program** funding is $600K ($550K after 8% indirect costs), of which 70% is spent on NSF fellowships for our students, on average 9 students at any one time. Each student annually receives a $30K stipend, tuition support, and a $2K research kitty. Our policy is to support each AB Certificate student for 2.0 years; the rest of their graduate study is covered by other faculty RA funds and UW TA's (typically for 0.3 to 1.0 year, depending on department). The remainder of the IGERT funds, which NSF severely restricts in their flexibility (e.g., foreign students are excluded), go primarily for non-faculty salaries (50% of our Coordinator, 20% of the new UW Interdisciplinary Programs "Diversity Recruitor", and 8% of the PI), assessment, international program (with Germany – Sec. 10.1.4), student travel for research and conferences, undergrad research jobs, annual workshop expenses, office expenses, seminar speakers, and short-term visitors.

NASA Astrobiology Institute funding is $1100K/yr, of which 110K is allocated to collaborators at other universities; after 52% indirect costs, this leaves $650K spendable at UW. These funds are distributed to 9 UW faculty for research expenses that include graduate student support, summer salary, publication expenses, travel, equipment, supplies, Education/Public Outreach, etc.

Our UIF award from the College of Arts & Sciences was for two new faculty positions (including their startup funds; commencing in 2001), plus $230K in startup funds for the Program during its first 2.5 years (e.g., 50% of two postdocs, 0.5 FTE for a staff member, recruiting, sponsorship of the highly successful 2001 Crystal Mt. Astrobiology Conference). What remains now is $28K/yr, which goes for graduate student and faculty travel to astrobiology conferences, office expenses, 1 month summer salary for the Steering Group Chair, and general needs for the program (e.g., Web and publication expenses).

UW matching funds to the NSF and NASA grants have been critical in our success, both in their quantity and greater flexibility. For example, we have 3 RA-ships/yr tied in to the NASA grant; these we use almost exclusively for the foreign students some of whom are among the best in the Program, but all of whom cannot receive NSF (IGERT) monies. The NASA grant also received, for example, matching equipment funds from the UW (e.g., for a mass spectrometer).

We have received extraordinarily wide support on campus. For the renewal IGERT grant, Table 3 (below) summarizes the UW matching that we have secured from 19 UW departments and colleges. This support is absolutely essential and is a measure of the confidence that the various units have in our program after its first five years. The main items include: (1) 50% of the Program Coordinator salary and web-development support (Vice Provost for Research); (2) space for the Coordinator and an RA slot each year for assessment (Sec. 9.2) (Graduate School); (3) 140 ft^2 of AB commons space for small seminars, meetings, and videoconferencing, and for graduate students to "hang out" together (Earth & Space Sciences Dept.)[3]; (4) space for an Astrobiology TA (Astronomy Dept.); (5) an RA slot for a minority grad student and support for recruiting of minorities, e.g., 50% support for a summer workshop on AB aimed at minority undergrads (Office of Minority Affairs); (6) a 5-day workshop cruise (once during the five years) on UW's oceanographic research ship *R.V. Thompson* (valued at $35K/day: School of Oceanography);

Table 3

UW Internal Support For The 2005-10 Astrobiology IGERT

Source	**Annual Value**	**Item**
Office of Research	$25K	50% Program Coordinator's salary
	3	Website work
Graduate School	---	office space, program administrator
Minority Affairs	28	one RA (minority)
CIRGE	28	one RA (assessment)
Minority Affairs	5	undergrad summer courses for URMs
Coll. Engineering	5	cash, general use
Civil/Environmental	1	"
Electrical	1	"
Aero/Astronautical	1	"
Coll. Arts & Sciences	15	"
Space Grant	12	50% of 3 undergrad research jobs
Atmospheric Sci.	1	cash, general use
Astronomy	1	"
	---	1/2 office for minority coord.
Earth & Space Sci.	---	140 sqft student commons space (yrs 3-5)
School of Medicine	10	cash, general use
Microbiology	3	"
Coll. Ocean & Fish. Sci.	15	Extremophile Lab support
Oceanography	2	cash, seminar series
Ship time	35	one day/yr of *RV Thompson* time
Total	**$190K/year, plus office and commons space**	

[3] This space was promised to be in the "new Johnson Hall", but we are now told by the ESS Dept. that the space may not be available when they move back in.

(7) support for the AB Extremophile Lab ($15K/yr: College of Ocean and Fisheries Sciences); and (8) an additional $52K/year in cash from participating colleges and departments for research expenses for grad students (especially the foreign students excluded from IGERT funds), teaching supplies, occasional faculty release for teaching AB courses, support of visitors (mostly seminar speakers), undergrad research jobs, computer and Web support, and other program needs.

8. Intramural Relations

Sustaining an interdisciplinary program such as ours is difficult in the academic environment of any large university, dominated as it is by an administrative structure where disciplinary departments are largely automonous and control the fate of individual faculty members and graduate students (in terms of hires and dismissals, salaries, promotion, allocation of resources). The Astrobiology Program has been dealing with this issue for the past seven years. The situation has improved over time, but remains a concern. We have been able to demonstrate in almost all cases, even to some initially skeptical departments, that our science is legitimate and that in fact our presence in their department leads to (a) interesting and exciting intellectual questions that would never have been proposed by faculty or students had it not been for the AB Program; and (b) excellent students being attracted into their departmental cohorts. We hear very few complaints of AB Certificate students being “distracted” from what they should “properly” be doing, i.e., departmental PhD requirements (which each AB student must satisfy). And of couse departments have come to appreciate our support of their students.

Despite this largely positive (or at least greatly improved) situation, it remains true that one of the main tasks facing the leaders of AB is to create and sustain ways to encourage the interdisciplinary contact essential to the Program. If this is not done, the academic structure described above means that, inevitably, the attentions of most AB participants will migrate back to their home departments.

As a largely self-selected faculty, we necessarily rely on our “local” AB faculty for the quality and strength of the AB presence in any given department. This usually works well, but nevertheless there are a couple of departments whose disciplines would fill intellectual gaps in our Program and where we have made attempts for inclusion, but have not yet been able to gain a foothold. Examples are Chemistry and Biochemistry.

Administering a program that involves us in four Schools and Colleges and about ten departments is of course a challenge. However, this too has improved with time as we’ve become a known quantity and individualized procedures have been established, e.g., in how student stipends are handled. Dealings with Chairs range from very positive to neutral; in fact two of our AB faculty *are* Chairs (Brown of Earth & Space Sciences and Bruckner of Aeronautics and Astronautics). Our relationships with the various Deans and the Provost's Office have also been supportive. For example, when Prof. Catling received a huge offer from Bristol University one year ago, UW put together a very good counteroffer (given its resources), but in the end the prestige and resources of an EU Marie Curie Professorship, as well as the chance to return to his homeland and start astrobiology there, was too much of a lure.

9. Self-evaluation

9.1 Past Assessment

(a) An Advisory Board of four prominent off-campus experts (D. Morrison and C. McKay of NASA Ames, K. Nealson of JPL/USC, and M. Greene of UPS) reviewed the entire program in 2001. They examined the curriculum, faculty participation, and student activities, including interviews with the students. That review (final report letter is included as Addendum D) was invaluable and resulted in suggestions for changes, some of which have already been implemented (e.g., a complete change in our approach to lab rotations by AB students, making the experience more doable and rewarding) and some of which are being implemented in our IGERT renewal (e.g., more practical experience for our students, from lab-engineering work to science writing).

(b) In early 2002 (after 2.5 years) we had an intensive, two-day site review by an NSF contract firm. The results were very supportive and encouraging, and we have adopted some of their suggestions, e.g., plans for improved performance assessment.

(c) Our greatest measure of success is the significant career development of our IGERT students themselves. Section 4.3 and Table 1 highlighted professional achievements of the AB graduate students.

9.2 Future Formal Assessment

With our IGERT renewal, we can now commence a more detailed, continuous, and quantitative analysis of the AB program's problems and progress. This effort will provide information on performance to three groups with different interests — students, faculty, and administration.

(1) We will continue with our **External Advisory Board**, asking them to evaluate progress twice during the next five years.

(2) We are considering adding an **internal UW committee** (from outside of AB) to review and advise on our policies and progress, say, every two years. The Urban Ecology IGERT Program has such a committee, but we are undecided, given other program reviews, as to whether it is worth everyone's time and effort.

(3) Prof. Maresi Nerad (Prof. of Education, Director of UW's **Center for Innovation and Research in Graduate Education (CIRGE)**, and Associate Dean for Research in the Graduate School) is a leading expert on Ph.D. education (Nerad 2004a, 2004b; Nerad & Miller 1996). She has been an integral part of the UW's Urban Ecology IGERT, for which she has recently designed both quantitative and qualitative assessment instruments. In joining us for our IGERT renewal, she is now commencing to likewise design and direct evaluation efforts for AB. Under her leadership CIRGE is developing a particular expertise in assessing IGERTs and other innovative doctoral programs on the UW campus. Thus, knowledge and experience from all UW IGERTs will be systematically collected and analyzed, and findings will then be distributed to NSF, the greater educational community, and IGERT faculty and students. Assessment will be as follows:

To understand the <u>differences between AB students and students with traditional PhDs</u> ("peers"), CIRGE will design, administer and analyze biannual surveys to both groups. These will inquire into educational experiences, career goals, and final outcomes, e.g., comparing first employment after the PhD.

In addition, CIRGE will <u>interview AB students annually</u>, inquiring about their motivations for studying under this IGERT, their expectations of program content and structure, their experiences with interdisciplinary learning and teamwork, and their recommendations for change.

Every other year CIRGE will conduct <u>interviews with faculty</u> about their goals, their evaluation of the program and their concerns.

In Years 1 and 4 of the IGERT renewal CIRGE will <u>interview deans and department chairs</u> of the participating faculty concerning the AB Program's impacts at college and department levels. We hope for heightened awareness of AB's success to significantly aid their commitment to program longevity beyond IGERT funding.

Each year short summary reports with recommendations for adjustments in the program will be distributed to all participants and discussed during a year-end meeting. In order to make our experiences available to the wider community, the critiques will also be posted on the AB website. In support of this effort the Graduate School is funding one RA/yr for CIRGE.

9.3 Areas of Concern

Here are our main areas of concern:

A. **Looking ahead to the post-IGERT era (> 2010).** We have been able to secure a 5-yr IGERT renewal, but NSF's policy is to award no third IGERTs. Thus in order to have a healthy Astrobiology Program beyond 2010 we must look to other sources of funding, in particular to support student RA's and fellowships.[4] By 2010-11 (we plan a no-cost extension to spread our funds out over six years) we ideally will have identified funding sources to support our students. One major category of such funds, especially for a field with intrinsic popular appeal such as ours, is private donations. Section 10.2 describes some preliminary plans along these lines, but we have not yet done enough thinking and acting about the post-IGERT era.

B. Faculty Demographics. We are a faculty that is self-selected. Through no design this has resulted in a strong tilt towards older faculty – a possible reason is that only faculty who are well established in their field can afford to spend time on an interdisciplinary and more speculative subject such as astrobiology (Rhoten & Parker 2004). Over the next five years perhaps four of our faculty will retire and it will by then also certainly be time for a change in leadership of the Steering Group. Who will fill these gaps? Furthermore, although we have recently been making some progress, how can we attract more younger faculty?

C. Cross-disciplinary education and research. A standard claim of ours (and others acknowledge it, too) is that the UW AB Program has by far the most *coherence* of existing AB efforts at major universities. What we mean by this is not that the individual UW researchers are markedly superior to their peers, but that the AB Program *as a Program* is a reality: (a) there exists a genuine "AB philosophy" in how we train our students, and (b) the students and faculty know each other and work together well. Despite our leadership in this respect, there are still many ways to improve. We want to go from strength to strength by further fostering the educational and research connections that make astrobiology so exciting.

D. Discrepancies between salary scales for grad students. Both faculty and students find it troublesome and inequitable that our AB students are paid at vastly different levels depending on the source of their funds and on their home department. IGERT fellowships, at an NSF-mandated stipend level of $30K/yr, are greatly to be prized. But we cannot award these to non-US citizens, who thus are

[4] NASA NAI funds are also vital to our program, but if in fact we are not renewed by NASA (although this is hardly our expectation), it would be a major blow but not a show-stopper, as we have other research funds through our individual faculty members' grants.

paid standard UW RA rates of only ~$19K/yr. Nor does NSF allow us to subsidize lower-paid RAs – to any recipient one must pay a full $30K or nothing. Furthermore, some departments pay their RA's at a 50% FTE level and others 60%.

E. Lack of contact with other UW interdisciplinary efforts. Our IGERT has been followed by three others at UW and yet there has been very little contact between the leaders, faculty, or students of these separate programs (despite repeated mutual declarations of intent), who certainly could learn a lot from each other about interdisciplinary education. All of the UW's various species of interdisciplinary programs could benefit greatly from more structured and more frequent interaction. One example was a informal meeting last May arranged by the Graduate School, which is the obvious locus for creating such across-campus connections. We hope that this sort of effort will continue.

10. Future Plans

Here we present some thoughts about the future, primarily of our educational program. New and continuing *research* directions are covered in Sec. 3 and Addendum B.

10.1 Educational initiatives

AB students and faculty together have identified new educational needs beyond those addressed in our first five years.

(1) <u>Engineering</u>. We must provide training beyond the core science of AB. In order that our students emerge ready to tackle real-world problems, we will add two innovative courses in lab techniques and engineering design (details below).

(2) <u>Science writing</u>. AB requires different writing skills: our students must learn to explain complex technical issues to lay audiences as well as to technical audiences not versed in multiple scientific jargons. We will engage AB students in scientific writing in novel ways, both for fellow scientists (as part of two new AB journals) and for the public.

(3) <u>International and domestic collaborations</u>. We will continue our leadership in AB through close collaborations and exchanges with other developing AB programs, both in the US and overseas (Germany).

(4) <u>A joint degree in "Department X and Astrobiology."</u> We plan to "upgrade" from an AB Certificate to such a joint degree.

(5) <u>ASTBIO 350 course</u>. We plan to develop an introductory course to Astrobiology for third and fourth-year science majors.

10.1.1 Initiative: Two new engineering/lab courses. We now realize that by concentrating primarily on astrobiological *science* our students have not gained sufficient practical experience. Furthermore, they would benefit from more teamwork experience, as is needed in the real world. We will teach our next cohorts of AB students lab and engineering practices in an environment of close teamwork by developing two new quarter-long courses that will occur in alternate years – every AB student must take one of them (with encouragement to take both); this new requirement will replace a present one for a "cognate" course chosen from a list of suitable AB-relevant interdisciplinary courses.

New Course #1 – The AB Lab Techniques course (ASTBIO 510), "From Stardust to Life," will include hands-on lab experiments from contributing AB disciplines such as Earth Sciences, Microbiology, Astronomy, Oceanography, and Engineering. Students will develop a unique combination of practical skills highly valuable for professional astrobiologists. Some labs will be deliberately designed to emphasize uncertainty, to give students a direct appreciation of dealing with ambiguous data, and to inspire critical thinking. One professor will run the course, with each experiment developed and taught by a faculty member expert in that field. Students will:

- Learn to interpret the composition and morphology of interplanetary dust particles under a scanning electron microscope (Prof. Brownlee).
- Synthesize organic molecules by using UV light to decompose methane in a bell jar, simulating the atmospheres of Jupiter, Saturn, and Titan (Prof. Gammon). They will also learn to interface sensors to remotely monitor the environment inside the bell jar (Prof. Mamishev). Students will then assess whether similar organic synthesis might have occurred in Earth's early atmosphere by examining how the process depends on the mixture of gases.
- Do an *in vitro* evolution experiment with a microbial culture, to understand evolution and microbial adaptation. This will involve placing it under selective conditions of their own choosing, and assaying it to see if they are selecting for/against a given trait (Profs. Leigh & Staley).
- Examine exotic extremophile traits in the Extremophile Lab (Profs. Deming & Baross). Students will also examine and interpret 16S rDNA gene sequences from their organisms (Prof. Staley).
- Examine fossils and consider the uncertainties that surround their interpretation (Profs. Buick & Ward). This lab will range from deciphering ancient microfossils to interpreting the fossil record of the Cambrian radiation of animal life.

- Interpret high-resolution images of Mars to assess the geological and climate context for possible life elsewhere (Prof. Gillespie), focusing on controversial features that may indicate a past Martian ocean.

New Course #2 – The Life-Detection Engineering Design course (ASTBIO 511), "Looking for Life," will be an interdisciplinary and practical team project centered on designing a "life-finder." A trial version of this course has been developed in Summer 2005 and will be offered in W06 by Profs. Mamishev (Electrical Engineering) and Morgansen (Aeronautics & Astronautics). The focus will not be on robotics technology, but on aspects that are uniquely relevant to detecting life. This course will be based on the Seaglider autonomous underwater research vehicles available at the UW's Applied Physics Lab (APL). These are ideal because they are currently used for oceanographic studies that require close teamwork between experts in the science goals and experts in engineering. Biologically relevant tasks will be specified (e.g., detect and locate signals such as heat or methane). Guided by AB faculty and APL personnel, interdisciplinary teams of students will design and construct sensors to work on a Seaglider in Puget Sound waters. Students will equip the robot with sensors, control its movement, and read out and interpret sensor data. This course will promote creative thinking to solve real-world measurement problems. Student teams will write project proposals (evaluated by faculty), do the building, programming and implementation, and write up results. Such projects work well elsewhere, e.g., robot soccer competitions and other educational settings (Polman *et al.* 2000). Although specifically aimed at AB needs, the course will also be open to and valuable for a wide variety of non-AB students. This mixture of students will help our AB students develop skills of working in interdisciplinary teams – invaluable in industry, government labs, and academia.

10.1.2 Initiative: Science writing

Several AB faculty are on the editorial boards of the new journals *Astrobiology* and *International Journal of Astrobiology*. We will give our students two innovative and powerful educational writing experiences in the form of published contributions to these journals: (1) we will commission individuals or small groups of senior graduate students to produce (under faculty guidance) original mini-reviews of well-defined AB topics; and (2) AB students will write summaries (as forewords) of standard journal articles, explaining each article's key results for scientists who are *not* specialists in the field of the article. We will also continue to encourage our students to take a UW course in science writing for the public; several AB students have already done so and written popular scientific articles – for example, "Extrasolar planets: Closing in on Earth" by John Armstrong in *Astronomy* magazine, 2003;

and “High-energy cosmic rays spark educational partnership” by Diane Nielsen in *Northwest Science & Technology*, 2002. Two of our AB faculty (co-I’s Ward and Brownlee), widely known for their popular science books (Sec. 4.4), will also mentor these efforts.

10.1.3 Initiative: Collaboration with other institutions

(a) NASA. We will strengthen our existing ties with NASA’s two lead institutions for AB — Ames Research Center and Jet Propulsion Lab — via a program of internships for AB students and slots at UW for Ames and JPL researchers to teach intensive short courses and spend sabbatical leaves. We will endeavor to have a strong representation of women and under-represented minorities among these visitors in order to provide diversity in role models for our students. We will also expand our connections to sister institutions in NASA’s Astrobiology Institute, via Internet broadcasting of seminars and classes and exchanging expertise via shared workshops and field trips. For example, the Univ. of Arizona hosted us for an astronomy-theme Workshop in March 2005 and we are reciprocating this autumn with a marine biology workshop. We are also budgeting for our *students* to host two AB conferences (over five years) that are limited to persons no more than one year past their PhD. In 2004 our students (almost totally on their own) played a key role in organizing and participating in such a conference, and we want to further encourage such activities, so important for building a discipline and promoting scholarly communication.

(b) Germany. An international program (funded by an NSF supplement to the IGERT grant) will add a significant new dimension to the total educational experience for our AB students, and help to develop a new generation of globally-engaged astrobiologists. It will: (1) expose them to differing strands of AB thought and research styles; (2) encourage them to think flexibly and to learn while in an unfamiliar cultural and educational environment; (3) enhance their confidence and improve communication skills through intellectual interaction with peers from different cultural backgrounds; and (4) provide them with an expanded network of contacts for current and future research and training opportunities.

To further these aims, we are developing strong ties with AB education and research in Germany. Germany is a leader in European AB, e.g., producing a recent monograph on AB (Horneck & Baumstark-Khan 2002). Several of us know German AB colleagues well. Prof. L. Thomsen of Bremen has taught in our School of Oceanography (with Prof. Deming), knows our AB program and the quality of our students, and is keen to foster exchange. The city of Bremen hosts the new International University of Bremen, with a focus on deep ocean environments (a major topic within AB), as well as the world-class Max Planck Institute for Marine Microbiology (another major AB topic).

We will hold biannually a one-week workshop, alternating between USA and Germany, modeled after the NATO Advanced Study Institutes: intensive tutorial lectures by faculty from both countries, with students presenting their latest research results. The second component of our international program will be UW student research visits of 2-12 months' duration in Germany. Already, one current IGERT student had a very productive summer in 2003 at Münster University developing physical models of Europa's subsurface ocean (**Vance & Brown 2004).

10.1.4 Initiative: A joint PhD degree in "X and Astrobiology"

After discussion among our faculty and students, we plan to "upgrade" our present Astrobiology Certificate into a joint degree with a title like "PhD in X and Astrobiology," where X refers to any of our participating departments. This resembles the degree offered by the Nanotechnology IGERT program. Given our present requirements for a Certificate, it appears to us that in fact we may even qualify for this type of joint degree with little or no changes from our present requirements (just a lot of paperwork to set it up!).

10.1.5 Initiative: An advanced undergraduate course

There has been significant demand for a 300 or 400-level course entitled "Introduction to Astrobiology for Science Majors," which will nicely complement our existing ASTBIO 115 course for nonscientists. In fact over the years several AB faculty have taught such a course under the rubric of "special topics" in their departments. We will now, however, institute a cross-listed ASTBIO 350 in order to give the course more stability and exposure. The ten-week syllabus will necessarily vary depending on the instructor, but we will insist that in no case does it devolve to only the astrobiological aspects of the instructor's own home discipline. In many cases it would best be team-taught, but this always raises difficulties with assigning appropriate teaching "credit" to the faculty members involved.[5]

10.2 The post-IGERT era and private funding

[5] Such "teaching credit" issues are yet another generic problem for interdisciplinary programs that must be resolved at the highest UW levels if interdisciplinary education is to prosper on this campus.

The most important aspect of IGERT funding has been the freedom it gives to a student – on an IGERT fellowship a student can roam, inquire and think beyond the usual bounds of project-oriented faculty research funded by an agency. This is the element that we would most like to continue in the post-IGERT era. We plan within a year to launch a campaign to locate foundation and individual philanthropic support for ten continual graduate fellowships in AB; this would require ~$250K/yr or an endowment of ~$5M.

In the past we have worked with the College of Arts & Sciences Development Office (primarily Dondi Cupp) in putting on events (lectures for invited guests followed by dessert and wine) aimed at nurturing potential donors. Together with our semi-annual newsletter (sample issues are in Addendum C) and public lectures, these efforts have garnered ~$15K in gifts specifically for graduate student support. These development activities take time to mature, but the intrinsic appeal of the more publicly exciting aspects of astrobiology makes it very attractive to potential donors. (Note that Paul Allen has donated a total of ~$30M for Search for Extraterrestrial Intelligence efforts in California!) Because the most likely sources of endowment funding are related to the world of business, we plan to produce a first-class illustrated "AB graduate education business plan" that could be given to any potential foundation or donor – in 5-10 pages it will state in plain language who we are, what we do, where we want to go, and what our needs are.

10.3 Further UW support

We have demonstrated in the preceding pages that the UW Astrobiology Program, although just starting its seventh year, has had significant successes and is transforming its graduate students, its faculty participants, its constituent departments and colleges, and the research field as a whole. We have accomplished in every way what we set out to do: to establish an innovative graduate program that is a world leader in an intellectually remarkable new field. This has happened because of hard work on the part of all concerned (including the students!), scientific acumen, significant support from UW administrators and outside agencies who placed their faith in us, and good timing regarding this exciting new field.

In order to further the stated missions of the UW with regard to teaching, research, and public service, as well as to act in accord with the UW President's and Provost's strong support of interdisciplinarity, we submit that the UW could do no better than invest further in the Astrobiology Program. Here we present a list of the resources, in approximate order of priority, that we require to maintain our leadership in the field and to go from strength to strength.

A. Faculty slot to replace the Catling position. In March 2005 Assistant Prof. David Catling (Atmospheric Sciences), whom we had hired with our UIF funds in 2001, left the UW for Bristol University in England. This was a serious blow to our program not only because he represented half of our core teaching effort, but also because he was an ideal AB faculty member – expert in several areas of research needed in our Program, an excellent interdisciplinary teacher and researcher, and well-connected to NASA missions. We request immediate authorization for a replacement so that we can advertise this winter for an Asst. or Assoc. Prof. faculty slot in order to have someone in place by Autumn 2006.

We propose to use the same format that was used in 2000-01 for the two successful searches that led to the hiring of Buick and Catling, namely an interdisciplinary search committee that seeks the right person for the program in terms of (a) firstly, their interdisciplinary astrobiological teaching and research abilities, and (b) secondly, the specific home department and chief research area. If all funds for this position come from Arts & Sciences, as they did for our previous hires, then the home department would be restricted to Astronomy, Atmospheric Sciences, Biology, or Earth & Space Sciences. It would be our preference, however, that the home department not be so restricted. The two research areas that would best complement those already existing among the AB faculty are planetary sciences and origin of life chemistry.

B. A third AB faculty slot in 2008. In order to teach our expanded undergraduate and graduate course offerings and to further diversify students' research options, we request that the UW invest in the near future in an additional junior position. Once again, *if* restricted to Arts & Sciences, the most needed research areas as we see it now include planetary sciences and origin of life chemistry, with the addition of extrasolar planetary astronomy. But if the Deans of Oceanography and/or Medicine and/or Engineering could be persuaded to potentially co-sponsor such a third AB slot, then other areas such as microbial evolution, extremophile ecology, and life detection instrumentation also become possible.

C. Matching money to stimulate private donations. As mentioned in the previous section, our highest priority in creating a viable Astrobiology Program post-IGERT is to raise private money for an endowment for graduate fellowships. The enticement of a strong UW match would significantly help.

D. Staff position for the AB Program Coordinator beginning in 2010. Today's IGERT pays for 50% of this position and the Office of Research chips in the other half. The promise now of a permanent staff slot for a Coordinator/Administrator would be an important vote of confidence in the AB Program, and start us on our way in the post-IGERT era.

E. Two TA quarters per year for ASTBIO 115. Each time we have taught our 5-credit introductory course for nonscientists (once per year) we have had to secure a single TA in an *ad hoc* fashion. This has also limited us to 2 sections (50 students) despite much stronger undergraduate interest that easily justifies 2 TA's (4 sections = 100 students). Continual funding of two TA quarters per year will enhance both undergraduate and graduate education (the latter through the teaching experience for our AB students).

F. 50% support for one AB post-doc for five years. Post-docs not only enhance research, but are vital mentors for graduate students and also often contribute to teaching (as we insist for all our post-doc positions). We are in the peculiar position that our IGERT grant includes two post-doc positions, but NSF allows only 50% funding for each one (*not* 100% for one person). If the UW picked up the other half of one of these positions, we could manage to fund the other half of the second one from research funds, and thereby have 2 post-docs continually in residence for the next 5 years, significantly enhancing the program.

We are grateful for past support and for consideration of these requests to invest further in the Astrobiology Program.

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ADDENDUM B

Five Areas of Research by UW Astrobiology Faculty & Students

[also see Sec. 3]

1. Instrument design and engineering
2. Habitability and evolution of planets
3. Asteroid and comet impacts – a cause of mass extinction events?
4. Limits of life
5. Earth's earliest environments: Development of microbial diversity and biological complexity

Research Area #1

Instrument design and engineering

(Bruckner, Mamishev, Morgansen)

The problem: AB students must not only ask questions, but also design equipment and conduct experiments to answer them. Designing life-detection techniques and devices that will give unambiguous answers is difficult, especially when the amounts of living material encountered may be extremely small (e.g., only a few cells). In trying to detect extraterrestrial life, the Viking mission to Mars in 1976 provided an important lesson: unexpected Martian soil and atmospheric chemistry gave false positives from life-detection experiments. Consequently, environmental parameters must also be measured so that we can distinguish living from non-living (abiotic) processes. Resolving this problem requires a combination of environmental sensors and life-sensing techniques.

Our approach: Designing suitable equipment and experiments requires engineering expertise. AB students gain hands-on experience in two broad engineering research themes, each covered by a new course (details in Sec. 10.1.1). Complementing these courses are two research areas offered to AB students: (A) sensing - detecting both life and the environments in which it may occur; and (B) autonomous control systems - autonomous robotics and their control systems for AB exploration.

A. Detectors for remotely sensing life. We are developing remote life-sensing techniques that can distinguish between living and abiotic chemical processes. They can be used both on Earth (deep subsurface; marine hydrothermal vents) and elsewhere (Mars, Europa, Saturn's moon Titan). We work on environmental sensors for critical parameters such as liquid or gaseous water, gases produced by microbes (e.g., methane), and gases that may be microbial energy sources (e.g., hydrogen). We also develop miniature sensors to detect carbon-based life. We investigate how biosensors can detect the broadest possible range of cell signals based on the unique chemical, physical and structural properties of living materials, especially those properties that change the cells' dielectric properties (e.g., electrical conductivity, resistance, magnetic properties). Biosensors typically comprise a thin film of material that is sensitive to microbial cells and is probed by electromagnetic waves and low frequency electric fields. Measurements of dielectric properties can be non-destructive and yet very effective (Mamishev *et al.* 1999)[6]. Examples include: (1) nonlinear broadband dielectric spectroscopy for monitoring cell activity; (2) dielectric spectroscopy and dielectrophoretic forces for measuring and manipulating DNA (Bakewell *et al.* 2000), proteins (Yokoyama *et al.* 2001), and bacteria (Ong *et al.* 2001); (3) single-cell dielectric spectroscopy (Sime-

[6] All references are at the end of the main Self-study text.

onova *et al.* 2002); and (4) non-invasive measurements on cells using electric fields in many ways (Mamishev *et al.* 1996).

B. Control systems. Environments to search for life are distant and often extreme, such as the ice cover and possible subsurface ocean on Europa, or the deep sea on Earth. The systems one sends to such places must be intelligent, robust, agile, and adaptable. For example, hydrothermal vents and other underwater regions are very promising environments to explore for evidence on the origins, existence, and development of life, both on Earth and beyond. Evolution has achieved an enormous amount of design and development for us to emulate; our intent is to generate novel bio-inspired systems that can improve the speed, agility and efficiency of robotic vehicles. The required systems must operate in dynamic fluid environments, and so we study biological systems (fish, birds, insects) to find optimal methods for robotic motion and station-keeping in fluids. Although many underwater vehicles use propellers (which give high thrust, but also high drag and low maneuverability), fish-tail type systems are more maneuverable, can turn in more constrained spaces, have lower drag, are quieter, and are potentially more efficient. Students are offered research opportunities in bio-mimetic actuators (e.g., fish-fin-like structures: Morgansen *et al.* 2002, 2001) and propeller systems, seeking to improve a robot's speed, agility, and stealth. This requires modeling fluid and actuator systems, sensing the fluid/actuator system, and designing control algorithms. Modeling of the fluid/actuator system must yield results (a) amenable to control-theoretic studies and algorithm design, and (b) accurately representing reality. Such systems are inherently nonlinear, and we work on models and algorithms to exploit this nonlinearity in autonomous operation (Vela *et al.* 2002).

Research Area #2

Habitability and evolution of planets,
both within our solar system and orbiting other stars
(Brownlee, Gammon, Quinn, Ward)

The problems: How common are habitable planets? On cosmic scales, where shall we look? By *habitable* we mean "capable of supporting some life form." Only certain regions of space, at certain times in galactic evolution, can produce habitable planets (Ward & Brownlee 2000, 2003). Space is vast and one should waste no time or resources looking for life where we believe it cannot possibly occur. Only recently, due to several breakthroughs in observations, have initial quantitative answers to these basic questions been possible. Refined Doppler measurements now give us a reasonable census of planets (about 150 known to date) around nearby stars (Marcy & Butler 2000). This information is key to estimating the number of planets available for life. Doppler searches are also supplemented by photometric searches, i.e., looking for planets that periodically eclipse their parent star. Furthermore, new observations (such as by the Hubble Space Telescope) give unpredented insight into the demographics of stellar birth and hence the environments where planets are made. Most stars are born in large complexes, which has implications for the formation and long-term stability of any planetary systems they may contain.

Advances in computational power now let models of planet formation make predictions testable by observations (e.g., Mayer *et al.* 2002) and let us compute a planet's orbit for the lifetime of its parent star. We can then estimate how long (and during what part of its evolution) a planet can stay in the "habitable zone" around its star. Combining improved observational data with theoretical advances lets us think far more broadly about the concept of habitability. Instead of considering merely the distance between a planet and its star, we can ask about larger issues such as whether there are particular times and places in our Galaxy where life-bearing planets can or cannot exist. Combined with knowledge of the evolution and abundance of planets, this will help us choose the best areas of our Galaxy for further investigation.

Remaining problems – gas giants and habitability. Although we are steadily able to detect smaller and smaller planets, there is still a huge gap (~15 times in mass) between Earth-like planets and the smallest extra-solar gas giant planets discovered to date. Gas giants are probably not habitable (although their moons such as Europa may be), but they greatly affect solar-system formation and evolution and their presence may imply the existence of habitable worlds. We therefore explore the dynamical connections between gas giants and possible habitable planets: (1) overall orbital stability of the known systems of giant planets (**Barnes & Quinn, 2004); (2) dynamical predictions of the location of (as-yet) undetected additional planets in these systems (**Barnes & Raymond 2004, **Raymond & Barnes 2005a); (3) influences of gas giants on planet formation in the "terrestrial zone" (the region around a star where Earth-like conditions are possible) (**Raymond, Quinn & Lunine 2004; **Raymond & Barnes, 2005b), including the case of close-in gas giant planets ("hot Jupiters") (**Raymond, Quinn & Lunine 2005); and (4) gravitational influences of giant planets on small bodies like comets and asteroids. These connections control where and how small bodies impact planets. In Earth's early evolution most of its water and atmosphere arrived via such impacts, which have thus been extraordinarily important during the evolution of Earth's life (see also Research Area #3). All of these factors profoundly affect the environment in which any life must evolve.

Other factors. There are many other factors contributing to habitability – e.g., (a) size of the planet (large enough to retain volatiles, and to drive long-term active tectonism and volcanism that could support microbial life); (b) delivery of water and organic compounds to the early planet via bombardment by asteroids and comets (**Raymond *et al.* 2004); (c) presence or absence of a stable orbit and obliquity ("tilt"), as needed to maintain a relatively stable climate over very long periods (**Armstrong *et al.* 2004); (d) feedback between surface properties, climate conditions and orbital parameters of a planet (**Armstrong *et al*. 2003); and (e) perhaps even periodic catastrophic events such as bolide impacts that are needed to create and maintain high variability of habitable conditions, thus promoting biodiversity and biocomplexity.

How to study these questions? Exploring each factor (and especially their interactions) requires cross-disciplinary collaboration and training. Our AB Program provides a rich intellectual environment for this complex work and is producing uniquely trained students. Current examples of AB student and faculty research include: (a) atmospheric scientists plus students of celestial mechanics, exploring how long-term variations in Mars's orbit affect its climate; (b) modelers of astrophysical dynamics plus paleontologists, estimating asteroid impact rates through Earth's history; (c) cosmochemists plus dynamical modelers looking for sources of Earth's water; and (d) oceanographers plus planetary scientists estimating probable conditions in Europa's ocean.

Research Area #3

Asteroid and comet impacts – a cause of mass extinction events?

(Buick, Ward, Warren)

The problem: Finding complex life. The probability of finding *complex* life (e.g., metazoan animals, higher plants, intelligence) on any given planet in a habitable zone is a function of how often complexity evolves from simpler life (frequency) and how long it survives (persistence). Mass Extinctions (MEs) are geologically brief intervals when a large fraction of a planet's biota is killed. Frequency and intensity of MEs may significantly influence both diversity and longevity of any complex biota.

Background. Impacts of comets and asteroids are important in AB - they impose strong constraints on where to look for habitable planets. Such impacts brought to pre-biotic Earth, from the outer solar system, some of the organic-rich materials needed for life to develop. Later, they severely altered the environment through impact shocks and addition of toxics (e.g., acids), markedly modifying the history of life. Other habitable planets will also likely have been both blessed and cursed by similar extraterrestrial impacts; we must understand how these effects vary in different planetary systems in order to know where complex life might exist around other stars.

Mass extinctions in general. MEs are most important to complex organisms (e.g., metazoans) because they are relatively fragile and easily killed. Microbial life is less susceptible to MEs -- in fact, once microbes invade a deep crustal or sub-oceanic habitat (Gold 1999; **Huber *et al.* 2002, 2003, 2004), they may be very difficult to eradicate. In general, the deep subsurface of any planet will be an effective refuge for life because it is insulated from even prodigious surface disasters, but due to small pore size it cannot be occupied by complex organisms. In contrast, surface life (even microbes) is susceptible to major planetary catastrophes, such as impacts of large comets and asteroids, excess radiation from a gamma ray burst or a nearby supernova, or short-term and catastrophic climate change (e.g., intense intervals of greenhouse heating or "Snowball Earth" episodes [Warren *et al.* 2002]). Perhaps Earth's surface was repeatedly sterilized during the Late Heavy Bombardment (which ended ~3.8 billion years ago), only to be re-seeded by deep-subsurface microbial life, or by rocks ejected by impacts and then returned to Earth (**Wells *et al.* 2002). If, however, *animal* life is wiped out, it cannot immediately restock from some underground reserve -- animals re-evolve only on time scales of hundreds of millions or even billions of years.

Earth's own mass extinctions. Judging from Earth's experiences, MEs could end animal life on any planet. On Earth there have been about 15 ME episodes during the last 500 million years, with each of the "Biggest Five" eliminating more than half of all animal species then extant. An unknown number of additional MEs may have also occurred during the earlier Archaean and Proterozoic eras. Because the frequency and severity of MEs would influence the evolutionary history of any planet having complex life, they are critical areas of AB study. MEs significantly affected the evolution of Earth's biota in two competing ways. In each ME, the paleontological record indicates that diversity was substantially reduced for the next several million years, yet was followed by extraordinarily rapid diversification, resulting in an equal or higher global biodiversity than was previously present, but composed of different assemblages of organisms. MEs thus seem closely linked to both diversity enhancement and biotic novelty, through elimination of existing taxa and opening of ecological niches: they are simultaneously foils and instigators to evolution and innovation.

Two major questions about MEs.

(1). Is there a critical number (and/or frequency) of MEs necessary to impact the development and/or subsequent diversification of metazoans? Our research deals with the relative importance of MEs as large-scale evolutionary phenomena. Because Earth's major MEs were so important in biotic evolution, we suspect that "too few" MEs may retard the rise of biodiversity. Yet too many MEs (or even one event of too great severity) will reduce diversity, or even eliminate complex life. Therefore we are critically examining Earth's biodiversity before, during and after several MEs of differing intensity, duration and spacing, to determine how diversity declined and arose again under these various scenarios.

(2). Precisely what caused the extinctions? Of the "Big Five" MEs, only the end-Cretaceous (K/T) event 65 million years ago has a known primary cause - asteroid impact. New but controversial evidence concerning the Permian-Triassic (P/T) and the Triassic-Jurassic (T/J) events suggests that these, too, were either partly or largely caused by the after-effects of impacts. Therefore, this research area tests the hypothesis that these events are associated with evidence of asteroid or comet impacts. Recently, researchers have found five new sites of late-Permian or late-Triassic age that are highly appropriate for paleontological and geochemical studies of the speed and causes of these two MEs. We are sampling for stable isotope and He^3 anomalies, and doing high-resolution magnetostratigraphic and biostratigraphic sampling surveys at terrestrial P/T and T/J sites in South Africa, marine P/T and T/J sites in Japan, and a marine T/J site in British Columbia.

We have already shown how environmental changes accompanying the P/T event 250 million years ago affected the evolution of mammal-like reptiles (Ward *et al.* 2000), thus indirectly constraining the possibility of the evolution of intelligence. However, the complexity of these changes makes it incorrect to invoke simple "single-causes" such as meteorite impacts as the *directly* responsible agent for the great P/T extinction. Instead, the fossil and geochemical records indicate complex, prolonged carbon-cycle perturbations and non-simultaneous terrestrial and marine extinctions (**Claire *et al.* 2002; *Buick *et al.* 2004). Single events may have been 'triggers' for much more complex environmental changes that more directly caused mass extinctions, re-directing evolution in the process. Similarly complex extinction events should be expected to have affected the course of life elsewhere in the cosmos.

Research Area #4

Limits of life

(Baross, Deming, Kelley, Staley, Warren)

The problems: What are the limits of "habitability"? Do limits of life on Earth indicate limits of life elsewhere? Our understanding of the adaptability of Earth's life has recently advanced tremendously. Among Earth's microbes are the *extremophiles* that live in extreme environments, from –20°C to > 120°C, at pH from 0.0 to > 10; in saturated salt solutions, at high hydrostatic pressures (> 1100 atm), and at radiation levels that would immediately kill any other life (Holland & Baross 2003). These known limits of terrestrial life are continually widening, most recently as a result of work done by our AB students (**Schrenk *et al.* 2003, **Junge *et al.* 2004). Some microbes use novel energy sources (e.g., electricity, Tender *et al.* 2002) or are active at pressures higher than any on Earth (Sharma *et al.* 2002). The fact that some of Earth's microbes can tolerate extreme conditions *not found naturally on Earth* is particularly relevant to AB. Even environments with very low water activities (e.g., high salt concentrations, desiccated or deeply frozen environments) have live microbes. In fact, a lower temperature limit for the survival of microbial life may not even exist (Price & Sowers 2004).

Our approach. We assume that extraterrestrial life may well resemble Earth's life in two ways: it will exploit similar carbon and energy sources, and it will exist under conditions that can host life on Earth. We research: (1) microbial diversity, physiology, and metabolism in Earth's most extreme environments; (2) microbial strategies for growth or survival under extreme conditions; and (3) potential biosignatures for use by robots to detect life (Area #1). Our research sites include frozen Arctic environments, deep (high-pressure) sub-seafloor habitats, and hot hydrothermal systems (which may resemble past or present conditions on Mars or on icy moons such as Europa).

We emphasize realistic *combinations* of extreme conditions rather than single factors (**Schrenk *et al*. 2003, 2004; **Junge *et al.* 2004; Deming & Eicken 2006). During biofilm formation, we focus on survival strategies such as motion (motility of bacteria, often seeking surfaces), attachment, and alteration of a host surface. We consider the extreme physical and chemical characteristics of solar system bodies (e.g., Mars, Europa, Titan) that only partially overlap terrestrial conditions. Truly exotic examples include extremely high-pressure environments that allow for ice to form at 20 to 80°C; brines that stay liquid below –30°C or above 200°C; and Titan-like conditions where organic solvents replace water.

(1) Deeply frozen sea-ice environments. We examine life in some of the coldest of all natural ice formations, *wintertime* Arctic sea ice (**Junge *et al.* 2001). In winter the top layers of sea ice often contain tiny pockets of brine liquid down to –35°C. Those we've examined house intact microbes, respiring and making proteins in 20% salt at –20°C (**Junge *et al*. 2004). Some bacteria are even motile at –10°C (**Junge *et al.* 2003), and many survive with the aid of organic polymers outside the cells (exopolymers) that provide protection against freezing (*Krembs *et al.* 2002). Pure culture studies of *Psychromonas ingrahamii*, a sea ice bacterium, have been found to grow at –12°C, the lowest temperature yet reported for growth (*Breezee *et al.* 2004). These findings, made by graduate students and postdocs active in the AB Program, suggest these hypotheses:

A. In Arctic sea ice containing pockets of liquid brine, a temperature threshold exists below which active microbes shift from a motile to an attached life style.

B. Organic exopolymers on a microbe in ice facilitate attachment, provide a physical barrier against high salt concentrations, and help metabolic activities to continue.

These testable hypotheses imply where to search for life in deeply frozen environments (look for minerals or other attachment particles) and what to try to sense (exopolymers as biosignatures).

(2) Looking for extraterrestrial life. Two promising nearby candidates for life, Mars and Europa, are both deeply frozen at their surfaces. To better design life-detection systems for frozen environments, we work with a "model" lab extremophile, the psychrophilic marine bacterium *Colwellia psychrerythraea* strain 34H, which grows readily at –5°C, is motile to –10°C, and produces organic exopolymers. We know its complete genome (*Methe *et al.* 2002), which lets us use comparative molecular biology (Area #5) and biotechnology (**Allen *et al.* 2002). We also bring novel cold-adapted organisms into culture, testing them under increasingly severe conditions. We are expanding beyond our Extremophile Laboratory to *in situ* experiments in Arctic winter ice (**Junge *et al.* 2004). Our programs take students into the Arctic for work outside their own disciplines – for example, in addition to AB/Oceanography students Eric Collins and Llyd Wells, AB/Geophysics student Steve Vance spent six weeks on an icebreaker in 2003-04 collecting winter sea-ice samples for extremophile work. With new partners from Engineering (Research Area #1) we plan to develop new ways to deploy experimental set-ups and sensors within the ice. We aim to identify compounds and structural aspects of ice that could be biosignatures for life in frozen extraterrestrial environments.

(3) Hydrothermal vent environments. Seafloor hydrothermal systems have some of the most extreme environmental conditions on Earth, including (simultaneously!) liquid water at > 400°C, acidic pH, extremely high concentrations of heavy metals, and high hydrostatic pressure (*Baross *et al.* 2006). Water-rock interactions in vents generate carbon and energy sources that support entire microbial communities in the dark *without photosynthesis*. Microbes exist in biofilms throughout the structure of active sulfide chimneys, even in zones that have experienced temperatures much higher than the known upper growth temperature (121°C) for a cultured hyperthermophile (**Schrenk *et al.* 2003). Most of these microorganisms have been detected with RNA probes, indicating that they may be viable and active. These findings suggest at least two hypotheses:

A. Thermophilic and hyperthermophilic (living at > 90°C) microbes derive key inorganic nutrients by altering insoluble minerals, e.g., calcium phosphate-based apatite.

B. Associations between microbes (e.g., in biofilms on minerals) enhance microbial survival under extreme conditions.

These testable hypotheses imply strong links between geology, chemistry and microbiology in studying the origin and evolution of life in Earth's early extreme environments (Research Area #5).

(4) Life in the dark (without photosynthesis). A nearby, deep hot biosphere may exist today outside of Earth – on Mars or under Europa's ocean. We need ways to detect and identify life there. Our strategies for isolating new hyperthermophilic microbes use unusual transition metals as electron acceptors and address newly discovered high temperature and high pH environments (*Kelley *et al.* 2001, *2004; **Schrenk *et al.* 2004). Mineral products could be important biosignatures. We emphasize isolating organisms that obtain all their nutrients from minerals and testing for the temperature limits of life *in situ*. Our AB students are critical in this research as we have hydrothermal vent expeditions and opportunities for them scheduled for upcoming years. AB students will also train with engineering faculty to design experimental devices and sensors to detect mineral-based biosignatures in present or past high-temperature environments.

Research Area #5

Earth's earliest environments:
Development of microbial diversity and biological complexity

(Baross, Buick, Leigh, Stahl, Staley)

The problem: In searching for life elsewhere, we must be able to recognize it at any evolutionary stage. Terrestrial life, as our only example, must guide our ideas about how alien life might evolve. But across the Universe, planets are in various evolutionary stages. Most Earthlike planets probably do not resemble *today's* Earth, but rather Earth's various past stages, which exhibited *only* single-celled organisms for over 2 billion years. Therefore, we concentrate on Earth's oldest and most primitive life forms, their relics in Earth's most ancient rocks, and their environmental impact on the planet.

Our approach: Study Earth carefully. We examine fossil and extant life, concentrating on two core issues: diversity and complexity. Earth's biological and paleontological records (Area #3) are our best proxies for the general development of planetary habitability and of life. Earth's environments have changed radically over time, yet life developed and persisted. We concentrate on the simplest organisms and their structures, because they evolved long ago (> 3 billion years; Shen & Buick 2004) and have diversified and thrived despite changing conditions. Our work on early environments, evolution, diversity, and complexity covers five main topics:

A. Microbial genomes. DNA sequences of today's microbes can tell us about the emergence and diversification of the major lineages of Earth's life, most of which has always been, and is today, microbial. We use comparative genomics to: (a) understand alternative sources of nutrients and energy for primitive life; (b) identify primitive metabolic interactions that supported early microbial communities and fostered biological complexity; and (c) evaluate alternative mechanisms of evolutionary innovation (i.e., lateral gene transfer). This approach tells us whether genetic change through Earth's history has matched the sequence of changing environmental conditions and how life today reflects its ancestral features.

B. Cell ultrastructure. Life on Earth is diverse and complex (Staley & Reysenbach 2002), but we do not understand how that complexity evolved. There are many apparent discontinuities in the development of biocomplexity, most notably the origins of: (a) organelles allowing respiration and photosynthesis; (b) the eukaryotic nucleus and cytoskeleton; and (c) multicellularity. To study these, we measure the distribution of key genes coding for these features among simple prokaryotic organisms to determine the antecedents of the trend towards complexity (Jenkins *et al.* 2002).

C. Microbial mats and biofilms. Earth's microbial mats and biofilms are layers of microbes that grow on surfaces in water (Teske & Stahl 2002), sometimes under extreme conditions (Research Area #4). These communities were important for much of Earth's history, as evidenced by ancient stromatolites (sedimentary structures built by microbial mats), and therefore may be important on other watery planets. These attached microbial communities were likely important for evolutionary innovation because they provide high diversity and high population density, thus imposing strong selective pressures and promoting lateral gene transfer and symbiotic associations. We study both modern and ancient microbial mats, their ecology and evolution, and their environmental impact.

Another type of biofilm, termed *desert varnish*, is formed on rocks in arid regions. These coatings, which are rich in iron and manganese oxides, resemble iron-rich coatings seen on Mars. Although desert varnish may not be produced by biological activity, unique biological signatures incorporated in desert varnish will provide a useful comparison with coatings from Martian rocks when they are available for examination (**Perry *et al.* 2003, **Perry 2005).

D. Precambrian fossils and biogeochemistry. Earth has supported life for at least 3.5 billion years, but the early record is poor and controversial. Through isotopic and molecular fossil ("biomarker") studies, we have dates for several important innovations in microbial metabolism (Brocks *et al.* 1999). This information allows us to date some key branch-points on the "Tree of Life," the overall genealogy of terrestrial organisms (Shen & Buick 2004). Much biochemical complexity, and most of Earth's high-level microbial diversity, arose very quickly after the end of the Late Heavy Bombardment ~ 3.8 billion years ago. We infer that microbial life on any planet could radiate equally rapidly, but our picture of early evolution is still very incomplete. Hence our studies focus on poorly known time periods (> 3.5 billion years ago), unexplored metabolisms such as novel CO_2-fixing and unusual metal-based pathways, and ancient biogeochemical cycles such as that of phosphorus (**Harnmeijer & Buick 2004).

E. Earth's environmental evolution. The physics and chemistry of any planet's atmosphere, hydrosphere and surface lithosphere reflect the co-evolution of its biological, geological and astronomical influences. Together, they indirectly monitor and record life's activities. To use such features to study life elsewhere, we need to know how these systems interacted during Earth's history. We are examining the progressive oxygenation of Earth's atmosphere as a proxy for the evolution of important microbial redox reactions (Rasmussen & Buick 1999; **Claire *et al.* 2004) — both oxygenic photosynthesis and methanogenesis are important (Catling *et al.* 2001). Finally, new studies of atmospheric pressure early in Earth's history (as inferred from structural features in lavas) may help us measure how biogenic greenhouse gases maintained a warm surface environment (~ present conditions) even when our Sun was 20-30% dimmer than today.