SESSION 1: TALKS -- BEICHMAN, WOOLF, BOSS

Chas Beichman talk. NASA's science program or theme, The Search for Astrophysical Origins, has as one of its fundamental goals to look for life: in extreme environments on Earth, to understand the limits of life; throughout the Solar System, but especially on Mars and Europa; and beyond the Solar system. The latter goal, of course, is the subject of this meeting. We should all keep in mind:

• For the biologists: planets are now thought to be a common outcome of the star formation process—and there is much evidence to support this concept;
• For the astronomers and other physical scientists: life on Earth is very hardy and able to exist and prosper in a wide variety of what had been previously thought to be harsh environments;
• For all of us: the ingredients that we think are necessary for life, are widespread throughout the Universe; and
• Life can impact its home planet's environment so strongly as to be observable over such large distances.

Star formation is a large and growingly successful area of study in astronomy today. Many protostars have been detected, and there is lots of evidence for gas/dust disks around these protostars, including, recently, solar-system sized disks. IR and radio observations show an abundance of complicated organic material in the interstellar and circumstellar environments. Over the past few years, planets have been detected around more than a dozen stars, now, including a multiple-planet system (in Upsilon Andromeda). So the astronomical context for the Pale Blue Dot is developing nicely.

However, we need to extend the search for planets. Astrometry is one promising alternative to radial velocity searches. Ground based systems in operation or in development include the Palomar Test Bed Interferometer, the Large Binocular Telescope, and the Keck Interferometer (in the Northern Hemisphere), with SIM (Space Interferometer Mission) scheduled to carry this capability into space by roughly the middle of the next decade. Eventually we expect to be able to achieve the microarcsecond sensitivity necessary to astrometrically detect an Earth mass planet in a 1 AU orbit around a solar type star 10 psc (about 30 light years) away.

We want, of course, to find habitable planets, so we need to search in the right size range, surface temperature range, and probably ensure that the planets are not tidally locked to the parent star. For a G type star the habitable zone is at roughly 1 AU from the star, corresponding to an angular separation on the sky of 0.1 arcsec at 10 psc.

The search strategy is likely to be to first survey the nearby stars for those that have terrestrial sized planets in the habitable zone; then (or at the same time) to get enough spectral information to determine those that have atmospheres; and then to target the most likely of those for more detailed spectroscopy, to search for biosignatures.

At least two missions are being studied that will directly detect and study planets: TPF (Terrestrial Planet Finder) and Darwin or ESIM (European Space Interfometer Mission ???). In either case the light from the planet would only fill a single pixel (picture element or 2-dimensional resolution element) and then with only a few infrared photons/sec. The star will be between a million (in the IR and longward) to a billion (in the optical) times as bright as the planet, and it is likely that dust in that system will produce a fairly bright background against which the planet must be detected.

An illustrative concept for TPF would consist of an interferometer comprised of 3.5 m telescopes, separated by 75 m (or more), orbiting at roughly 1 AU. The expected lifetime would be about 5 years, with launch planned for roughly 2010. TPF is intended to make use of nulling interferometery to block most of the light from the star, with the goal of 'nulling' 10**-5 to 10**-6 of the stellar light, while transmitting essentially all of the planetary radiation in the system's bandpass.

Even with this rather impressive facility, the signal-to-noise ratio and resolving power for spectroscopy are likely to be quite modest. Therefore it is important to search for indicators of habitability and biosignatures that can be seen even when the noise is high and the resolving power is no more than 50. (Resolving power = R = $\lambda/\delta\lambda$.) With this illustrative system, a good rule of thumb for the required integration times is: detection of planet in 2 hours; determination that it does or does not have a substantial atmosphere in 2 days; search for spectral evidence of life in 2 weeks. Therefore, during its lifetime, TPF should be able to survey all likely stars out to about 15 psc or 50 light years, select the best candidates for finding evidence of life, then follow up on these with longer integrations.

This is a daunting task, but both NASA and ESA are developing and flying the technologies that will be essential for the success of TPF. SIRTF, NGST, ground based interferometers and SIM, plus Space Technology Three, are all examples of missions that will develop and test critical technologies.

The goal of TPF is to provide data to the biologists (and atmospheric chemists) who will be best able to evaluate the observations in terms of evidence for life. Therefore this community must participate actively in defining the mission. We need to know: what makes a planet habitable and how that can be studied remotely; what the effects of biota are liable to be on the atmospheric spectrum; what false positives to expect; what the evolutionary history of the atmosphere is liable to be; and, especially, what are **robust** indicators of life.

Nick Woolf talk. Biology is going to be driving our studies for the foreseeable future. This talk, therefore, is going to be addressed to explaining to the biology community what it is that astronomers can do for them.

First: light comes in quanta or bundles of energy, called 'photons'. The energy of a photon is linearly proportional to its frequency, or inversely proportional to its wavelength. So an optical photon is more energetic than an infrared photon, which, in turn, is more energetic than a radio photon. Secondly: photons arrive at a random rate and that produces what's called 'shot noise'. So, if we are measuring on average about N photons per event, we can expect that number to fluctuate by roughly N**1/2. In other words, if the event is characterized by N = 100, then we can expect no better than about 10% accuracy. To get 1% precision spectrometry will require integrating long enough to receive 10,000 photons—in each spectral channel. We need to take that into account when designing our experiment.

Thirdly: the radiation coming from a warm object has a peak in its spectrum (the spectrum is called a 'black body' or 'Planck distribution'), where the wavelength (or frequency) of the peak depends only on the temperature. As the peak is approached from the long wavelength side, the intensity and number of photons emitted rise, but for wavelengths shorter than this peak, the intensity falls off rapidly and, since the energy per photon is growing towards shorter wavelengths, there is a cutoff in the flux of photons as well. The net effect is that most of the radiation and also most of the photons from such a body come out near the peak of the black body spectrum, so this is where one would prefer to observe if at all possible. Since most atmospheric observations will be of absorption against the warm planetary surface, it is important to observe in a spectral regime where there are enough photons from the planet to give good statistics.

The radiation from a planet has two parts: at short wavelengths the planet reflects the star light, while at long wavelengths the planet glows by its own heat. Typically for terrestrial planets the split is about 50-50 in terms of energy. In terms of numbers of photons, there are substantially more of them in the long wavelength portion of the spectrum, and that makes it easier to observe in the long wavelength, thermal portion of the planetary spectrum.

Now we're interested in molecules and how they interact with the radiation field. They do this through their rotation, vibration, or by the arrangement of their electrons. In the typical case where the planetary surface is warmer than the atmosphere, these molecules will be seen in absorption. The heavier a molecule is, the longer will be the wavlengths of its characteristic rotation and vibrational transitions. The lines will be seen to group into 'bands', where each band corresponds to a given vibrational transition which is split into a series of equally spaced rotational transitions. At low resolution, a band will just appear to be a broad continuum absorption feature. Electronic transitions of molecules, which tend to be rather weak, occur typically in the visible and uv regimes.

To interpret a spectral feature, astronomers make use of a technique called 'curve of growth'. As the amount of material is increased, the strength of the absorption feature grows linearly with this amount. This happens until all of the light inside the natural linewidth is absorbed, and then the strength does not change with increasing amount, until the collisions with other atoms broaden the wings of the lines. Here the amount of other molecules in the atmosphere is important. Absorption can then occur in the wings of the line, and the strength of the absorption grows as the square root of the number of molecules in the line of sight. These three portions of the curve of growth are called: linear, saturated, and damping parts of the curve of growth. Because of the dependence of the damping part of the curve on atmospheric pressure, it is feasible, though oftimes difficult, to unravel the pressure distribution of the atmosphere from deconvolving spectral lines.

This technique then allows us to determine relative amounts of material above the ground in a cloud free planet, or above the cloud deck in a persistently cloudy planet, or, if the cloud cover is partial, we can find some sort of average. There are other approaches that can be used if there is a major condenseable in the atmosphere, essentially a ‘bootstrapping’ method.

To see trace constituents, it will eventually be necessary to go to much higher spectral resolution. Somewhere around R ~ 50,000 or more, to see the faint narrow features on the linear part of the curve of growth.

The kinds of features that might possibly be observed, in analogy with the Earth’s atmosphere, include CO, O3, CH4, NO, even some of the anthropogenic products, e.g. freons. But these latter would require very high spectral resolution and/or very high precision, and that means a very large telescope, in fact an impractically large telescope in the near term.

So to repeat: the planets are very faint, the star is very much brighter and quite close by, and the dust in the system is likely to be a few 100 times as bright as the planet in our beam, or even brighter, and what’s more, the dust near the planet will be at roughly the same temperature. The contrast ratio between the planet and the star is quite a bit more favorable in the IR, longward of the peak of the thermal emission from the planetary surface. Now, since the spatial resolution of a telescope of a given size will vary inversely with the wavelength of the light, the background due to dust in the system will get stronger, even relative to the emission from the planet as the observing wavelength is increased. This is because the planet typically would not be spatially resolved, even though the dust cloud is, so a larger beam on the sky would already be receiving all of the planet’s radiation, but would collect more radiation from the dust.

Even with a very large aperture telescope, straightforward imaging of the planetary system is fraught with great difficulty. This is why the choice, at least in the near-to-mid term is to use interferometry to both spatially resolve the planet from the star and to null out the light from the star. Recent developments in telescope technology, especially lightweight optics, give increasing confidence that we can successfully develop a TPF-like observatory. And we have convincing evidence from ground-based observations that the nulling technique actually works and produces useful data.

Indirect detection of Earth sized planets—i.e. gravitational lensing or occultation—can detect such planets, but generally does so by looking over a wide range of distances, but only a narrow field of view. Therefore, though the general distribution of planets can be determined, these techniques do not directly tell us about nearby planetary systems.

Alan Boss talk. Up till very recently, theoretical work on planetary system formation has tended to focus on understanding the Solar System, with far less effort devoted to predicting what different systems might be associated with other stars. This tended to develop a bias in favor of systems very much like the Solar System, so the properties of the newly discovered extra-solar planets have taken the theorists by surprise. But they are working hard to recover!

This talk summarized the current data on extra-solar planets, then discussed what this means in terms of our Solar System and others. It covered the theory of planet formation, again, mostly applicable to our Solar System, ranging from terrestrial planets, which are thought to be well-understood, outward to the Gas Giants, where there are two main competing theories of formation, and on to the Ice Giants, Neptune and Uranus, where the theories do not yet successfully explain how those planets might have formed.

All detections of extra-solar planets so far are by the radial velocity method, which gives a lower limit to the mass, and are for stars very much like the Sun. There are about 20 or 21 planetary objects (as of today), including the first planetary system that has been detected—Upsilon Andromeda—around a solar-type star. There is a break in the mass distribution of these planets and the lower end of what is probably the brown dwarfs, from ~10 MJ to ~40 MJ. If this break persists, than that would provide an excellent discriminant between objects that form as planets and objects that form as stars (even though they are ‘failed stars’, i.e. do not have enough mass to ignite nuclear fusion in their interiors).

And if the 10MJ objects are planets, our current theoretical understanding would say that they are Gas Giants, though we have no direct evidence of that as yet.

The sensitivity of radial velocity detection limits the available parameter space to large masses and short period orbits, so it is not surprising that this is where the current set of extra-solar planets lies. To go to much smaller masses is not feasible with the radial velocity method, so we must look to other techniques to get us into that part of phase space. The astrometric method searches for planets by looking for the regular motion of the parent star on the sky, i.e. perpendicular to the line of sight. It is conceiveable that this method will allow us to find planets of substantially lower masses, and an important part of SIM's mission is to do just that.

So, major milestones in this observational field so far are: (1) the first detection of an extra-solar planet around a main sequence star (a planetary system was previously discovered, orbiting a pulsar, but that is not likely to be of direct relevance to this workshop); and (2) the first detection of a planetary system, three large planets in orbit around Upsilon Andromeda. We hope the third major milestone will be to find a Jupiter-mass planet orbiting far enough away from the parent star (several AU or beyond) to allow a terrestrial sized planet to be orbiting in the star's habitable zone.

Our current understanding of the theory of terrestrial planet formation begins with a rotating disk of gas and dust in orbit around the newly formed star. Random motion of the grains in the disk brings them into contact, they stick together, eventually compacting to form 'pebbles'. This process continues up to the formation of km-sized objects, after roughly 10,000 years.**SOMETHING WRONG WITH THIS NUMBER!** At that point self gravity becomes important, increasing the cross-section for collisions by a large factor, and consequently speeding up the process. This leads to 'runaway accretion', where the largest of these km-sized bodies will dominate and accrete the others, plus any remaining material in the disk, growing up to roughly the size of the Moon in about 100,000 years. After a few million years or so, the disk will be dissipated, probably in such a way that the gas flows onto the protostar. The final phase of accretion, which takes ~ 100 million years or so, consists of the dominant body assimilating many of the asteroid and moon sized bodies, which have been disturbed from their nearly circular orbits by gravitational interactions with the larger bodies in the system; eventually the dominant bodies grow to terrestrial-like masses.

George Wetherill has modeled the final phase of this process, i.e. from lunar-sized to terrestrial-sized bodies, and he varied some of the relevant parameters, e.g. mass of the Sun (or parent star), mass of the disk, etc. His 'standard model' starts with a solar mass star and defines the mass and angular momentum of the disk to equal the current Solar System values. It is important to note that, since the process is intrinsically stochastic, one needs to run a substantial number of models, and the conclusions that one then draws are statistical. Typically his calculations predicted a mass and orbital distribution very much like that of the terrestrial planets we see now: Earth, Venus, and Mars. Now, if the parameters are varied from their standard values, things change. In case the surface density of the disk is reduced/increased, then the resulting planets are proportionately less/more massive. And there would be no lack of terrestrial planets in the habitable zone.

The giant planets play important role in this process. For example, if Jupiter is moved in to 3.5 AU, then the accretion process is perturbed, preventing the formation of planetary bodies down to 1 AU. So it's likely that no planets would be able to form in the habitable zone. Note that, according to these calculations, the currently known extra-solar planets are in systems where no terrestrial-sized planets should exist, at least in the habitable zone. On the other hand, if the outer planets are removed from the system, lots of Earth-mass objects can form and in a variety of orbits. Without a Jupiter to measureably perturb the star's motion, such systems would be difficult to find at present.

Formation of the Giant Planets: The most popular model, the core accretion model, again starts with the grains in the disk accumulating, eventually reaching km-sized bodies. Now, since the gas/dust in the disk are lost within a million years or so, then the growth process from km-sized to much larger sized bodies (on the order of 10 Mearth) must take place quickly so that there is material left to accrete onto the core. In this model that again happens through a runaway accretion. At that point the gas in the disk is hydrodynamically unstable, collapsing onto the core in less than 1 million years. So when the disk is dissipated, a system of giant planets is left behind. Using the Wetherill method to grow the cores, leads to problems: only in 1/9 of the cases did these calculations lead to a large enough core in less than 10 million years, and those objects had large eccentricities, unlike the planets in the Solar System. To get the process to go faster requires increasing the initial surface density of the disk over the 'standard value' in Wetherill's models. That seems to work, though the process is very sensitive to the surface density of the pre-planetary nebula. And it does predict that no giant planets will form inside of ~ 5 AU, which is in spectacular disagreement with the present observations. So, if this model is correct, there must be other processes going on, and dynamical migration of the giant planets in toward the central star would probably be required.

Another method for producing giant planets is by gravitational instability, if the outer disk is cold enough. Calculations have been done to investigate the consequences of that hypothesis. They show that the process is feasible, also quite rapid. This method seems to require some sort of perturbation or 'trigger' to get it going.

For the outer planets—Uranus and Neptune—the state of the theory is far more primitive. If a disk density at these distances is chosen, which is consistent with the rest of the solar system, then it takes far too long to get the cores to form. On the other hand, if cores of an appropriate mass are arbitrarily inserted into the model, the results are reasonably consistent with the observations, provided that some method of damping eccentricities is also assumed.

So, the theory of terrestrial planet formation is in good shape, though the process is stochastic, so it is impossible to predict a specific outcome for a given set of initial conditions. The understanding of gas giant formation and evolution is not as advanced, and we don't know exactly how they are formed, or how their orbits evolve after they form. And we know very little about the formation of the ice giants. Nearly all the calculations to date have been done in an attempt to match the Solar System mass and orbital distribution, so much work remains to be done to extend these calculations to what we might see in other systems.