ON THE NUMBER OF GALACTIC PLANETARY SYSTEMS

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ABSTRACT. The discoveries of small particulate clouds surrounding several young stellar objects may be the first direct indications of ongoing planet formation in the Galaxy. If these clouds are indeed the initial stages of new planetary systems around the stars, then planetary systems are probably not rare occurrences around stars and may even be quite common. The evidence for these clouds and their interpretation as young planetary systems is reviewed and discussed in the context of estimating the probability for planet formation around solar-mass stars.

1. INTRODUCTION

Although planets may not be the only homes for extraterrestrial life, lifeforms like the ones on Earth almost certainly inhabit planets, so the search for extrasolar planetary systems is an important part of SETI. To argue that life is a likely occurrence in the Galaxy, we need not require that most stars possess planetary systems, only that the frequency of planetary systems around stars is not vanishingly small (e.g., Harrington 1982). Even if only one star in a thousand has planets suitable for the evolution of life, there are still more than ten million main sequence stars in the Milky Way where life might evolve, and the discovery of even one nearby star with a planetary system would make a very good case that there are plenty of planets in the Galaxy which might harbor life. Because small, nonluminous planets are extraordinarily difficult to detect with conventional instruments, the lack of any good evidence for extrasolar planetary systems is not yet a persuasive argument against the existence of life outside the solar system.

Planets probably form at the same time as their host stars (see, for example, Gehrals 1978). In typical scenarios, both angular momentum and magnetic pressure create disks of gas and dust orbiting a newly forming star. A combination of gravity and "stickiness" then enlarges small condensations in the disks to planets as the stars evolve. We know very little about the details of this evolution, but most astronomers believe that some kind of extended disk precedes the

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formation of planets. Such disks may be easier to observe than the planets themselves, and if planets occur frequently around other stars, disks should occur at least as frequently around protostars. Therefore, the detection of preplanetary disks might provide a tractable means of estimating the number of planets in the Galaxy.

This year brought two important discoveries that indicate planetary systems are common. The first was the discovery of solid particle debris around the main sequence stars, Vega and Fomalont, revealing clouds of matter like our own zodiacal particles but with considerably more mass (Aumann et al. 1984; see Aumann's discussion in this volume). It appears that solid matter exists in concert with many older stars, suggesting planets exist as well. The second was the detection of clouds of small particles seen in highly magnified images of young stellar objects in what look like preplanetary disks. Of less than a dozen objects observed, particulate clouds show up in three: HL Tau, R Mon, and L1551 IRS 5. This is a high percentage, and although the sample is somewhat biased, the implication is that conditions around many young stars are conducive to the formation of planets.

In this talk, I will discuss the circumstellar matter around the very youngest stars. To be of interest for SETI, we must show that planet formation is a plausible evolutionary path for this matter and that the occurrence of such matter near ordinary stars, that is stars not too different from the Sun, is probably common enough to safely assume planets will form around some of these stars. Fortunately, the observations give us just enough information to provide useful insight into both questions.

2. PROTOSTARS

We have many examples of pre-main sequence stars (Wynn-Williams 1982). Stars of approximately solar mass dominate by number the more luminous massive stars. Low mass stars or stellar objects evolve in much the same way as the Sun, making them interesting objects for the study of planetary systems that might harbor life. High mass stars burn out quickly on galactic time scales. Were Earth to have formed around a ten-solar mass star, intelligent life could not have evolved as it did.

The youngest examples of solar mass stars are the T Tauri stars. The common view is that these stars are in a radiative Hayashi phase slowly contracting to the radius characteristic of the main sequence (Herbig 1952, Walker 1959). This opinion is not universally held (e.g., Gold 1984; Mercer-Smith, Cameron, and Epstein 1984), but almost everyone agrees they are in an early pre-main sequence stage. Because they are young but otherwise sun-like, and very common, T Tauris are excellent candidates to search for preplanetary matter.

Indirect evidence for disks of small particles around some T Tauri stars came relatively recently. For example, Cohen (1983) argued that HL Tau, a pre-main sequence star in the Taurus dark cloud, is surrounded by a thin disk of small particles (dust grains), based on his early observations of spectral features in the star's extinction curve. Similarly, the light from these stars is often polarized, as it would be if some of the light is reflected from particles close to the stars (Vrba, Strom, and Strom 1976; Bastien 1982), HL Tau being one of the best examples. Unfortunately, the regions very close to the stars are complicated by gas flows in and out of the stars and are poorly understood. Spectra of the stars show several regions of remarkably different temperature similar to the photosphere, chromosphere, and corona in the Sun but with much more matter in the hot components. No well-accepted model explains all the data.

The matter velocities close to the stars suggest there aredifferent kinds of disks. Mass loss is common from T Tauri stars. Some stars show both mass outflow and mass inflow as if two different streams of gas are channeled by the surrounding matter. Mundt and Fried (1983) recorded several remarkable images of the gas flows near HL Tau and DG Tau showing that the outflowing matter is confined to narrow channels, almost pencil beams, as if mass is lost through a tube. These data and others (e.g., Canto *et al.* 1981, Jones and Herbig 1982) could mean the inflowing or orbiting matter near the stars condenses first into dense toroids or fat disks which collimate matter ejected from the stars. Although I personally think this is not the actual situation around the stars, the apparent axial symmetry of the gas streams compels us to discuss disk-like symmetries for the surrounding matter.

The Taurus dark cloud is approximately 200 pc from the solar system. Disks with solar system dimensions, 50 AU in radius, say, subtend angles only a few tenths of an arcsecond. Since these angles are close to the diffraction limits of the largest optical and infrared telescopes, and well below typical seeing-limited image sizes, the search for these disks demands careful imaging techniques. Fortunately, optical and infrared imaging instruments are undergoing a revolution. It is now possible to make observations at or close to the fundamental limits set by telescope sizes. The first high-resolution imaging led to the discoveries of solid matter close to several T Tauri stars described in the next section.

3. THE PARTICLE HALO IN HL TAU

Small particles in preplanetary disks will reflect some of the light from the central stars giving the stars a diffuse, extended appearance. Early photographs of pre-main sequence stars sometimesrevealed diffuse, extended regions (e.g., Herbig and Rao 1972, Mundt and Fried 1983), but the pictures rarely had the resolution needed to examine physically interesting regions for planet formation. Two methods for increasing image resolution, the application of maximum entropy criteria for recovering information from blurred pictures and the use of speckle interferometry to reach the diffraction limit of large ground-based telescopes, are relatively recent innovations leading to the discovery of the scattered light in the vicinity of HL Tau and

R Mon. Both maximum entropy image reconstruction and speckle interferometry provide limited and somewhat complementary information about the scattering regions, but the conclusions derived from the observations are substantially the same.

HL Tau is a pre-main sequence star, probably no more than 10^5 years old, having recently formed from the surrounding cloud material. Because of its relative youth, planets probably have not had time to form. It is, however, an excellent candidate to search for circumstellar particles in a preplanetary disk. Its mass is similar to the Sun's, making it a "typical" star of the sort around which intelligent life could evolve as it has on Earth. And as Cohen (1983) points out, the presence of small particles close to the star may already be inferred from its spectral characteristics.

Both cleaned images (Grasdalen et al. 1984) and speckle interferograms (Beckwith et al. 1984) show that HL Tau is surrounded by a small, diffuse region where tiny particles scatter the starlight. The scattering region appears elongated along a line east-southeast to west-northwest on the sky. The axial ratio is approximately two to one, very much like a disk which is tilted to the line-of-sight. The shape of the images suggests a particle disk near the star.

The size of the scattering region is approximately 200 AU by 300 AU. Pluto's orbit has a diameter of 80 AU, so if we assume the particles are in a disk, with 300 AU being the size of the major axis, the disk is about four times larger than the known size of the Sun's planetary system. The scattering particles do not reside in a thin plane, as discussed below, and it is entirely possible that the scattering region represents only the outermost "fat" part of the a disk which is thin at small radii and increases in thickness as the radius increases. There may well be an inner region containing substantial mass that will show up with careful observation.

The circumstellar particles reflect quite a large fraction of the near-infrared starlight. At a wavelength of 2 μm, at least 20% of the light comes from the scattering region. Since particles can only scatter the light which reaches them, the large scattered fraction implies that particles obscure an equally large fraction of the sky as seen from the star. If HL Tau radiates isotropically over 4π steradians, ~ π sr contain scattering particles close to the star. The "disk" around this object must be relatively fat with a ratio of thickness to diameter of at least 1 to 4.

Solid particles scatter short wavelength radiation more efficiently than long-wavelength radiation when the wavelengths are larger than the size of the particles. This effect is responsible for the reddening of galactic starlight and the blueing of light reflected by interstellar dust. The fraction of scattered light around HL Tau is a strong function of the observing wavelength, being larger at the shorter wavelengths, implying the scattering particles are no larger than about 1 micron in diameter, and possibly much smaller. Typical interstellar dust grains are about ~ 0.1 microns across, so the particles are probably normal interstellar grains. Since the circumstellar matter almost certainly comes from the dark cloud surrounding the star, the presence of small grains is expected, and may mean most of the solid material has yet to form planets, not a surprising result in view of the youth of the star.

The size of the images, the fraction of the scattered light, and the information about the particle sizes already provide enough information for quantitative estimates about the state of the circumstellar matter (Beckwith et al. 1984). For example, the mass of solid matter is at least equal to the Earth's mass and may be much greater. This mass is, of course, about the same as the mass of solid material residing in all the terrestrial planets. Most of the solar system mass, excluding the Sun, is hydrogen in the giant planets Jupiter and Saturn and amounts to about 400 times that of the Earth. Since the normal ratio of hydrogen mass to grain mass in the interstellar medium is approximately 100, we infer an unseen mass in gaseous hydrogen around HL Tau of 100 Earth masses. Thus, the circumstellar region has both a similar size and a similar mass to the solar system, and there is likely to be even more matter around the star than observed in the scattering region. Given the uncertain nature of conditions in the early solar system (e.g., Gehrels 1978), the correspondence between the circumstellar region of HL Tau and that suspected for our own Sun's birth is striking.

One might worry that the observed region is simply a transient property of the gas flows near HL Tau and does not represent the early stages of planet formation. While it is impossible to predict now whether planets will actually form, we can examine some of the obvious alternatives which will not lead to planet formation. It might be that dust condenses in the outflowing wind making a seemingly stationary scattering region in a constantly expanding shell. In fact, there is much more dust than is likely to be formed in any outflowing wind, unless estimates of the mass loss rate from the star are too small by factors of one thousand or more. The role of continuous accretion of matter from the surrounding clouds is less clear. I do not think it likely that accretion of gas and dust directly onto the stars will give rise to the observed scattering regions. It may be that relatively stationary disks, fueled mainly by accreting matter, form around the stars. The accretion energy released in the disks might puff them up to appear thick and may even give rise to the observed mass loss. Or perhaps the thickness results from warping caused by non-coplaner orbits at large radii. The disks could form planets after accretion and mass loss has slowed down or stopped.

Small particles in orbit around main sequence stars are affected by stellar radiation. In principle, constraints on the particle size distribution result from considerations of particle orbit lifetimes. By assuming the Poynting-Robertson effect determines orbit lifetimes for the particles around Vega and Fomalont, Aumann et al. (1984) derive a minimum particle size and a corresponding minimum mass for the circumstellar matter. Such arguments place no strong constraints on the particles around HL Tau and R Mon for two reasons: The stars are much younger than Vega and Fomalont, so even short orbital lifetimes are allowed, and there is almost certainly gas mixed with the dust, so radiation is less effective in changing particle orbits. The relative youth of the protostars allows a much wider range of circumstellar matter than is expected near main sequence stars.

If the amount of gas around these stars is close to the value calculated by using the interstellar gas to dust mass ratio, there is enough mass in the disks to stabilize them against disruption from the outflowing winds, even if there are no additional stabilizing factors such as magnetic fields. The environments around T Tauri stars are notoriously violent, harboring mass outflow, inflow, and energy to ionize some fraction of the hydrogen. Yet the scattering region is probably sufficiently massive and opaque to be immune to disruption by these strong forces.

To demonstrate the matter around HL Tau is, in fact, bound to the star, one must show the gas velocities are less than the escape velocity from the circumstellar region. The gas 100 AU or more from the star should be cold, ~ 100 K, say. Interferometric observations of millimeter wave lines from molecules such as CO and CS might provide this information and are possible from Owens Valley or Hat Creek. Should the gas velocities be close to the stellar velocity and less than the escape velocity from the extended region, it will provide strong evidence that the matter is bound to the star, not undergoing disruption, and quite plausibly in a state which can form planets during the next epoch of pre-main sequence evolution.

4. THE CHANCE FOR EXTRA-SOLAR PLANETS

There are currently at least three candidates for preplanetary disks: HL Tau, R Mon, and L1551 IRS 5. In addition to the many main sequence stars surrounded by solid particle clouds (Aumann, this volume), there is the discovery of scattered light from a particle disk in β Pictoris reported by R. Terrile and B. Smith in a recent press release. The picture of α Pic provides the best evidence for a disk structure in any of these clouds, since it appears to be almost edge on. The sample of stars chosen for IRAS observations is relatively unbiased, whereas the samples of T Tauri stars examined by Beckwith et al. (1984) and Grasdalen et al. (1984) and the stars observed by Smith and Terrile (according to the news coverage) are very biased. Although it is premature to estimate the statistical chance of finding planetary disks around pre-main sequence stars in any detail, we can already guess whether this chance is large or small.

The meager statistics so far suggest gravitationally bound clouds with solar-system dimensions are not rare. Of the six T Tauri stars closely examined for circumstellar particles, three show reasonably good evidence for this matter. There is indirect evidence for axisymmetric geometry in these six stars, principally the observations of highly collimated gas outflow and linearly polarized light from the stars. There is good evidence for axisymmetry in the surrounding matter of many other low- and high-mass stars, but they have yet to be examined in enough detail to reveal circumstellar disks. Similarly, the IRAS observations of nearby main sequence stars show particle clouds around many. If this matter is the remnant of more massive clouds that formed during the pre-main sequence phase, then gravitationally bound clouds must have been common in the early lives of these stars. All of these discoveries have come in the last year or so, the time when high-resolution images at visual and infrared wavelengths and sensitive far-infared photometry from IRAS first became available. It is difficult for me to believe that these discoveries could come so quickly after the introduction of new techniques unless particle disks are a common property of young stars.

From the standpoint of SETI, this argument is indeed exciting. If stars often bind enough matter in clouds of solar-system dimensions, it is reasonable to suppose that planets occasionally form. As mentioned above, as long as the chance for planet formation is not vanishingly small, there will be many sites to harbor life forms similar to those on Earth. Should Earth be the only place where life exists in the Galaxy, it is probably not for a lack of other good environments, for it may be that planetary systems are nearly as common as stars.

There is a reasonably good chance that some of the questions pertaining to planet formation from circumstellar disks might be answered by the end of this decade with the many new instruments under construction. It is not yet clear how the violent gas motions present in many T Tauri stars help or inhibit planet formation, nor how magnetic fields, accreting matter, and the presence of companion stars affect the chance for planets. The Hubble Space Telescope will give us pictures of these regions with much better resolution than presently possible. The resolution will be further increased by using the new imaging techniques like speckle interferometry on 10- and 15-meter class telescopes planned for the future. Direct studies of the gas motion may come from millimeter wave interferometers, the VLBA, or even by combining imaging with spectroscopy at visual and near-infrared wavelengths. Such data might make the theoretical problems associated with the study of planet formation tractable.

Of course, the best way to estimate the number of planetary systems in the Galaxy is to directly detect other planets. This goal it has been difficult to achieve. That our best estimate of the number of planets might come from indirect detections of the planetary precursors or remnants underscores the importance of exploring new techniques for information about stars and their environs. And it should give the optimists in the SETI community some encouragement that seemingly intractable problems will find solution and provide us with insight as to whether or not we are alone in the universe.

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