A REVIEW OF THE SCIENTIFIC RATIONALE AND METHODS USED IN THE SEARCH FOR OTHER PLANETARY SYSTEMS

David C. Black
Theoretical Studies Branch
NASA Ames Research Center
Moffett Field, CA 94035

ABSTRACT. Planetary systems appear to be one of the crucial links in the chain leading from simple molecules to living systems, particularly complex (intelligent?) living systems. Although there is currently no observational proof of the existence of any planetary system other than our own, techniques are now being developed which will permit a comprehensive search for other planetary systems. The scientific rationale for and methods used in such a search effort are reviewed here.

1. INTRODUCTION

Five years ago in Montreal the seeds of this Symposium and I.A.U. Commission 51 were planted (Papagiannis 1979). While the passage of five years has not led to the discovery of extraterrestrial life, it is significant that the theme embodied in this Symposium provides the basis for what is perhaps the broadest interdisciplinary research effort in the annals of science, including the scientific disciplines of astrophysics, biology, chemistry, and geology. One can not say with certainty that extraterrestrial life will be discovered in the next twenty years, however, one can say with certainty that because of efforts to detect extraterrestrial life and to understand the origin and nature of life generally, humankind's knowledge of the universe will be much greater than it would otherwise be.

It is, I think, a measure of the key role that knowledge about other planetary systems plays in the search for extraterrestrial life that the first session of the Symposium is devoted to this topic. This role comes about for a couple of reasons. First, planetary bodies are generally thought to be necessary if life is to evolve to a complex state; they may even be necessary for the origin of life. Planets can be thought of as "cosmic petri dishes". Second, it is now clear that we know how to detect other planetary systems and that the technology is or soon will be at hand to permit a comprehensive search effort using a wide variety of techniques. I indicated earlier that one can not say with certainty that extraterrestrial life will be discovered in the next twenty years. However, one can say with confidence that, if some of the techniques and instrumentation that I and others in this

M. D. Papagiannis (ed.), The Search for Extraterrestrial Life: Recent Developments, 33–41.

https://doi.org/10.1017/S0074180900146327 Published online by Cambridge University Press

session will discuss are developed and implemented, we will be able to discover whether other planetary systems exist within a distance of several tens of light years from the solar system. It is important to realize that, perhaps surprisingly to many participants in this Symposium, there is currently no observational evidence for the existence of any planetary system other than our own.

The remainder of this paper is concerned primarily with a discussion of the scientific rationale for conducting a comprehensive search for other planetary systems. A brief review of the general types of observational techniques that can be used to conduct a search is also given. A more comprehensive discussion of these issues can be found elsewhere (Black 1980).

2. SCIENTIFIC RATIONALE FOR A SERACH FOR OTHER PLANETARY SYSTEMS

The interdisciplinary character of a search for extraterrestrial life was noted above. A similar statement can be made about a search for other planetary systems. The results from a comprehensive search (I will say more about what constitutes a "comprehensive" search in the remarks to follow) would significantly effect three areas of scientific study; the origin of the solar system, the formation of stars, and last but not least, the search for extraterrestrial life. A discussion of the rationale for a search is best cast in the context of the significance of results from a search.

Most modern hypotheses as to the formation of the solar system envision the process as a natural consequence of the formation of the Sun. If one assumes that the Sun was formed in the same way as were other stars of similar mass then this causal relation between the formation of the Sun and the formation of the planets which revolve about it has a truly profound implication; most if not all single stars should be accompanied by a retinue of planetary companions. The extent to which individual planetary systems are alike, or the extent to which the solar system is typical of planetary systems, is unknown. The important point is that if this causal relationship exists, observational evidence concerning the existence and properties of other planetary systems can play a central role in constraining theories of star formation.

Perhaps the major challenge facing students of the solar system is understanding its origin. It has become clear in recent years that if we are ever to understand that origin, even in very general terms, we must obtain detailed observational information concerning other planetary systems. The necessity for this type of data derives from the fact that it is only through such information that we will be able to meaningfully test theoretical models for the origin of the solar system, and develop alternative models should the current ones be inadequate. Two examples of possible results from a search serve to illustrate this point in specific contexts.

An obvious feature of the solar system is that the giant, volatile-rich planets are located at great distances from the Sun; distances at which temperatures are currently below that required for condensation of the more abundant volatile species in a solar composition gas.

This is often interpreted as implying that the Sun was well formed and self-luminous at the time of planet formation. Discovery of Jupiter-like planets revolving around other solar-type stars, in orbits ranging from one to a few AU, would cast doubt on this generally held inference from solar system properties.

A significant fraction of modern theoretical studies of the solar system focus on the problem of how planets like Jupiter are formed, or more specifically, why Jupiter has the mass that it does. One possible result of a serach program could be discovery of a planetary system associated with a solar-type star that has only low-mass planets in its outer regions, and with a relative distribution of planetary mass similar to that found in the satellite system of Uranus, for example. Such a finding would suggest that studies directed toward explaining specifically the magnitudes and distribution of planetary masses found in the solar system would be misguided.

There are three general scientific objectives for a search program for other planetary systems:

*Discovery of another planetary system.

*Determination of the statistical properties of planetary systems.

*Determination of the detailed properties of individual planetary systems.

These objectives are listed in the order of increasingly more detailed information content. It should be noted that each of these objectives involves "planetary systems", not "extrasolar planets". This point is developed in more detail below. Let us consider each objective in turn.

Confirmed discovery of another planetary system would certainly provide impetus to vigorously pursue more ambitious searches. One need only recall the excitement both in the scientific and popular press when IRAS discovered evidence for simple dust orbiting the star Vega to get a sense of the likely reaction to confirmed discovery of another planetary system. However, simple discovery would not provide detailed quantitative characteristics concerning planetary systems as a general phenomenon. If we are to make progress on questions of planetary system and stellar formation, we require the kind of information provided by accomplishment of the second and third objectives listed above.

The second general objective concerns statistical properties of planetary systems. Emphasis here would be placed on such properties as the frequency of occurrence of planetary systems and the mass of the most massive planetary body as a function of the mass of the central star. It would be very important to know, for example, whether planetary systems occur with any star regardless of spectral type, or whether they tend to be found in association only with specific types of stars. Also of interest is whether planetary systems are found in conjunction with stars that are members of binary or multiple stellar systems, or are they only found in association with single stars. The long-lived nature of planetary systems (relative to the timescale thought to characterize the formative phases of a star's life) offers the possibility of using the type of statistical data mentioned here to gain otherwise unobtainable insight into the dynamics of these formative phases. Information on the mass of the most massive member of planetary systems could provide a first-order check on current hypotheses for the origin of the solar system.

Determination of the detailed properties of individual planetary systems is likely to be the most difficult of the general objectives. It will require data over a longer time span and of higher intrinsic accuracy than will the first two objectives. Of interest here are the orbital properties of the planets in individual systems, the masses and spatial distribution of planets within a system, and where possible, information on the temperature and composition of individual planets. Clearly some of these properties will be very difficult to obtain but it should be recognized that this third objective is likely to be the focus of research efforts of the twenty-first century.

Most, but not all, previous discussions of detecting other planetary systems have only addressed the question of detecting a "Jupiter-like" companion to other stars. The term "Jupiter-like" is sometimes used to denote an object whose mass and orbit about its central star are identical to those of Jupiter, and it is also used to denote an object whose mass is identical to that of Jupiter, but whose orbit about its central star is unspecified. Such an approach to the problem is not without basis; the most detectable planetary member of the solar system, employing any of the presently envisioned detection techniques, is Jupiter. The question arises, however, as to whether discovery of a "Jupiter-like" companion to a star is equivalent to discovery of another planetary system.

A more general form of this question is whether discovery of a single "planet-like" companion to a star constitutes discovery of a planetary system, where "planet-like" is here taken to mean any object whose intrinsic properties match those generally associated with planets in the solar system. It should be pointed out that there is considerable uncertainty regarding the frequency of occurrence and the mass distribution of binary stars. Simple extrapolations of data concerning binary companions to solar-type stars seems to indicate that a significant fraction (50-75%) of such stars which do not have stellar binary companions, do have substellar binary companions; companions that might otherwise be called "planets".

Our present understanding of the relationship, if any, between the formation of a binary system and the formation of a system like the solar system is rudimentary at best. Absence of clear theoretical guidance in the interpretation of observational data makes it essential that we place stringent requirements on the accuracy of observational data. Given that nature prefers to make stars in binary systems, a significant fraction of which involve substellar companions, it would not be too surprising to discover that a large number of stars have a "Jupiter-like" companion. However, although one might claim to have discovered an "extrasolar planet" by discovering systems of the type just described, there would be no convincing evidence that a "planetary system" had been discovered. Simply put, a system with a "Jupiter-like" companion could equally well be either of two things; a giant planet with yet undetected planetary bretheren, constituting a planetary system formed through the same general processes as our own planetary system, or a high mass ratio binary system. The distinction is important because the solar system is after all a system consisting of a star and nine principal planets, two of which (Jupiter and Saturn) are of comparable mass and comprise some 90 percent of the known mass of the planets. Statistics on properties of binary systems where one member is of substellar mass are important, to be sure, but their relevance to planetary systems is not at all obvious.

Throughout this discussion I have used the term "comprehensive search" without explicitly stating what I mean. Perhaps the best definition of a comprehensive search is that it is one which will address the second of the general scientific objectives of a search program, viz, provide a sufficient data base to permit a determination of the statistical properties of planetary systems. A corollary of this is that a comprehensive search is one from which null results would have great scientific significance. A practical implication of these requirements is that such a search must include hundreds of stars of a variety of spectral types, and it must be capable of detecting unseen companions as small as Uranus or Neptune (i.e., $\sim$ 10-15 times the mass of the Earth) to solar-type stars.

3. REVIEW OF POSSIBLE SEARCH METHODS

Detection of bodies with the low mass and luminosity that typifies planetary objects, especially over distances of several tens of light years from the Earth, is difficult. One can categorize detection techniques as being either direct or indirect. Direct detection techniques are those which sense radiation coming from an unseen companion to another star; the radiation may be thermal (infrared), or nonthermal (e.g., reflected visible light). Indirect detection techniques are those which monitor some observable property of a star (e.g., its motion) and permit inference of the presence of a companion or companions by virtue of patterns in that observable property. A variety of instruments are or soon will be developed which are potentially capable of conducting some level of search for other planetary systems. A full discussion of each of these instruments is beyond the scope of this review, but I will try to outline some of the techniques and indicate what appear to be particularly promising approaches to a comprehensive search.

Comparison of the spectrum from a large and relatively luminous planet, viz, Jupiter, with that of its parent star is provided in Figure 1. The contrast in brightness between planet and star is large, particularly in the visible part of the spectrum (Jupiter is nearly nine orders of magnitude dimmer than the Sun in visible light). When this is coupled with the fact that the angular separation between a star and a putative planetary companion is likely to be quite small (the angular separation between the Sun and Jupiter when viewed from a distance of 10 parsecs is 0.5 seconds of arc), one appreciates the extreme demands on telescope resolution for the direct detection of other planetary systems. At the present time there is only one telescope, the Hubble Space Telescope due to be launched in 1986, that has some potential for directly detecting other planetary systems in visible light. One of the focal plane instruments on the Hubble Telescope, the Faint Object Camera, has coronagraphic capability when used in the f/288 mode. This capability is provided by the presence of an occulting finger in the input image plane and a pupil mask in the transfer optics. The camera will be able to detect features that are nearly 17 magnitudes fainter than a bright point source object as long as those features are one arcsecond or more from the occulted bright source. Although this is impressive performance, it is not clear whether it is sufficient to permit detection of Jupiter-like companions even to nearby stars; it certainly is <u>not</u> adequate to permit a comprehensive search for other planetary systems.

The situation is somewhat better at infrared wavelengths where the contrast ratio is only about four orders of magnitude (see Fig. 1). However, as it requires a larger telescope to achieve a given level of angular resolution in the infrared than it does in the visible part of the spectrum, there remain significant problems for detection. At the present time there are no instruments that could undertake even a limited infrared search for Jupiter-like companions to nearby stars. There are two instruments that are currently being considered by NASA which have some potential here. One of these instruments is called the Space Infrared Telescope Facility (SIRTF) formerly known as the Shuttle Infrared Telescope Facility, and the other is called the Large Deployable Reflector (LDR).

SIRTF is a one-meter class, cryogenically cooled telescope with a sensitivity some three orders of magnitude greater than the highly successful recently flown IRAS telescope. The nominal spatial resolution of SIRTF, if it is diffraction limited at a wavelength of 30 microns, is about six seconds of arc, comparable to the angular separation of Jupiter from the Sun as seen from our nearest stellar neighbors ($\sim$ 1 parsec away). If this were the best that one could do with SIRTF, there would be very little hope that it could detect even large planetary companions to nearby stars. However, it was shown with the IRAS telescope that one can obtain what is being called "super resolution", that is effective spatial resolution in excess of that specified by the Rayleigh criterion. In some cases the IRAS science team was able to obtain nearly an order of magnitude better spatial resolution than one would have predicted. The success of this operation depends critically upon the point spread function (psf) of the telescope optics remaining constant over time. If it is, one can use the knowledge of the psf to in effect subtract the imperfect off-axis light surpression capability of the telescope and thereby obtain spatial resolution that is better than predicted on the basis of simple optics theories. Whether SIRTF will be sufficiently stable to permit the type of data processing required to obtain "super resolution" is moot, but if it is it will permit a search of our nearest stellar neighbors for the presence of large planetary companions.

The LDR will be an orbiting telescope 15-20 meters in diameter that would permit astronomers to conduct observations over a very wide wavelength range ($\sim$ 30 - 1000 microns). As a consequence of its large aperture, LDR will have a combination of sensitivity and spatial resolution that is unprecented at its operating wavelengths. In particular,

https://doi.org/10.1017/S0074180900146327 Published online by Cambridge University Press

LDR would be able to detect Jupiter-like companions to many of the stars that are within a few parsecs of the Sun, and it could detect young, and hence hotter, gas giant planetary companions to young stars such as those in the Ursa Major system. Current plans (hopes?) are that SIRTF will be launched in the early part of the next decade, and that LDR would follow some ten years later. In any case, it is clear that at the present time there are no instruments either soon to be available or on the perceivable horizon which will permit more than a modest direct search for other planetary systems. These instruments could discover very nearby planetary systems, but they will not be able to conduct the type of comprehensive survey that is essential for maximum scientific benefit from a search.

Some of the more exciting developments in terms of instrumentation and techniques that can be used in a search for other planetary systems are in the area of indirect detection. The two major techniques here are those of astromeric and spectroscopic observations. If a star has a companion(s), the center of mass (barycenter) of the system lies not at the center of mass of the star, and the star undergoes orbital motion about this barycenter. The displacement in a star's motion that is associated with this orbital motion can be detected in principle through very precise measurements of the position of a star as a function of time. A star that has no companions will appear to move in an approximately linear fashion across the sky whereas one with companions will appear to "wobble" as it moves because of the superposition of orbital and linear motion. Astrometric observations of sufficient accuracy could detect this "wobble" and thereby permit indirect discovery and characterization of unseen companions to a star. In a similar way, the orbital motion of a star with companions will give rise to a periodic Doppler shift in the spectrum of the star, a shift which can be detected in principle with very accurate spectroscopic observations.

Five years ago the accuracy of routine stellar spectroscopic observations was $\gtrsim$100 meters/second. In order to place that in perspective, the magnitude of the velocity effect on the Sun's motion due to the presence of Jupiter in only about 13 meters/second. However, recent developments in spectroscopic techniques and instrumentation, most notably at the University of Arizona and at the Canada-France-Hawaii telescope facility, now make it possible to conduct stellar spectroscopic studies at a level of accuracy approaching 5-10 meters/second, accurate enough to undertake a search for substellar companions to several tens of stars in the solar neighborhood. One of the positive aspects of this technique is that it can be conducted from ground-based observatories; there is no significant gain to be had by going to space. The spectroscopic search technique is best suited to discovering companions that are near their central star, that is, those with orbital periods that are short (less than 10 years). This means that a concentrated search effort using this technique could provide some very exciting discoveries within a few years after a systematic search program is initiated.

Current astrometric observations are accurate to a few millarcseconds over a year of observing. The amplitude of the perturbation in the Sun's motion due to the presence of Jupiter is 500 micro arcseconds when viewed from a distance of 10 parsecs. There are hopes that the accuracy of ground-based systems can be improved to a level of a few hundred micro arcseconds, adequate to detect Jupiter-like companions to many nearby stars. This gain in accuracy requires the construction of a new ground-based telescope along with the use of photoelectric detector systems of the type that has recently been developed at the Allegheny Observatory. While this would be a significant gain in performance, there appears to be a fundamental limit to the accuracy of most ground-based astrometric observations that is set by turbulence in the Earth's atmosphere. The exact level of this limit is not known, but all indications are that it is at the level of a few hundred micro arcseconds. In order to reach the full potential of astrometric studies, and to conduct a comprehensive search, one must go to space above the atmosphere. There are several instrument concepts, ranging from interferometers to more classical imaging telescopes, that appear capable of making measurements of the relative positions of stars with an accuracy of 10 micro arcseconds or better. This would be adequate to detect even Uranus-mass companions to most stars within a few tens of parsecs of the Sun.

An exciting prospect concerns use of the Space Station as an observing platform for an imaging astrometric telescope. Although the Station is likely to be too "noisy" in a vibrational sense for interferometers, it appears to be an ideal place to locate an imaging system which is very forgiving of vibrational motion. Further, the long-term stability offered by the Station matches well the needs for a long-term observing program, one that might span two decades, of the type envisioned for a comprehensive search for other planetary systems.

4. CONCLUDING REMARKS

The next few decades will certainly lead to exciting discoveries in a variety of areas of research. It is to be expected that many of the problems discussed at this meeting will be solved or at least made clearer during this time. There is little doubt that one area where major advances are foreseeable is in the search for other planetary systems. A decade ago when the topic of SETI and the nature of evidence for the existence of other planetry systems was being discussed in such a way that it lead to the programs that are currently under way, astronomers had just begun to develop the instruments that would permit a comprehensive search for other planetary systems. We now know how to conduct such a search, using a variety of techniques, and it is time to begin.

I have tried to outline here the principal scientific rationale and objectives of a search program. There is little question in my mind that a search for other planetary systems is one of the more significant undertakings of all time. It constitutes the final step in the Copernican revolution, and will provide the beginnings of a new discipline, planetary systems science. If the results from a search should reveal that planetary systems are rare, or even more extreme that no other planetary systems are detected in a search of our stellar neighbors within say 30 parsecs of the Sun, then we will not have the beginning of a new scientific discipline. For if the solar system was formed as a consequence of a rare event in the galaxy, not only will it be necessary to reject most of the current models of solar system formation, but it will also preclude meaningful scientific test of any hypothesis in the foreseeable future.

Whatever the outcome of a search, it will irreversibly and fundamentally alter mankind's perception of the universe in which he lives and his relationship to that universe. I personally look forward to the next few years with a sense of great excitement.

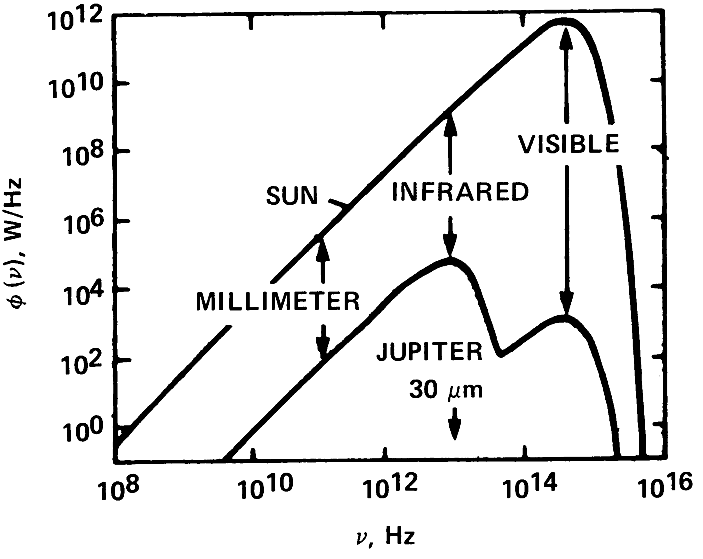

Figure 1: Plot of the radiated power per unit frequency as a function of frequency for the Sun and for Jupiter. The curves are idealized in that they are for black bodies.

REFERENCES

Black, D.C. 1980, Space Sci. Rev., 25, 35.

Papagiannis, M.D. 1979, Strategies for the Search for Life in the Universe, Astrophysics and Space Science Library, Vol. 83, ed. M.D. Papagiannis, (D. Reidel).