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Exozodiacal Dust Workshop

Conference Proceedings

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Goals of the Workshop

One of NASA's fundamental goals is to search for evidence of life outside of the Earth. An important element of that goal is to search other stellar systems for terrestrial-sized planets in the so-called "habitable zone," image those planetary systems that contain such likely sites for life, and through spectroscopy or other means, look for unambiguous signs of the presence of life. To this end, conceptual studies are already underway to define the Terrestrial Planet Finder (TPF) mission. TPF will be a space-based spatial interferometer, working at infrared wavelengths to detect and characterize Earth-like planets in orbits around nearby stars that are within 10-15 pc of the Sun. Launch of TPF is planned for 2011.

It is expected that a significant limitation to unambiguous planet detection and study will be background thermal emission from warm dust within a given planetary system--the exozodiacal dust cloud. At present, the amount, distribution, and composition of the exozodiacal dust, particularly the warm component, is essentially unknown. This lack of knowledge leads to significant uncertainties in the requirements on TPF for such fundamental parameters as sensitivity and angular resolution, with matching uncertainties in the final design.

Consequently, the goals of this workshop were quite specific: to understand how dust around its target stars will affect TPF's performance; to summarize the current state of knowledge of exozodiacal dust clouds, as well as the local zodiacal cloud; to identify what additional knowledge must be obtained to help design TPF for maximum effectiveness within its cost constraint; and, finally, to recommend ways to obtain that additional knowledge, with an eye towards minimizing the cost required to do so.

The workshop was structured around several sets of review talks, followed by working sessions, where the attendees were divided into smaller groups to attack specific topics. The group sessions were designed to respond to the following questions:

- Where do we need to increase our knowledge of the exozodiacal clouds?
What measurements will have the biggest impact?
- What parameters of the exozodiacal clouds are important for designing TPF?
- What current and approved missions, observatories, etc., can be used with or without modification to improve our knowledge of the exozodiacal clouds?
- What new instruments, experiments, theoretical investigations, and/or missions might be required to fill in critical information on the exozodiacal clouds?
- What recommendations should we make to NASA, National Science Foundation, or other groups to enable the acquisition of the observations and development of the models and theories of the exozodiacal dust needed to optimally design TPF?

About This Document

The Workshop on Exozodiacal Dust held at NASA Ames Research Center on October 23-25, 1997, benefited from contributions of individual invited speakers, poster presentations by attendees, and numerous discussions involving both small groups and the entire gathering of Workshop attendees. All of these contributions are represented in this final report.

Each of the invited talks is represented by 2 to 4 pages of text supplied by the speaker, a few key figures, and copies of the view graphs used by the speakers during their talks. The poster contributions are gathered near the end of the report and are represented by 1 to 2 page summaries supplied by the poster presenters. During each of the small group discussions, a designated scribe recorded the key issues that were considered and prepared view graphs that were subsequently presented to, and discussed by, the attendees. In consultation with various meeting attendees, the editors of this report used the view graphs provided by the scribes to produce brief summaries of the small group discussions. These summaries are placed more or less chronologically throughout the text.

The editors wish to thank a number of people without whom this document and the meeting that generated it would not have been possible. The program benefited immensely from excellent invited speakers selected by the Scientific Organizing Committee (SOC). A listing of the members of the SOC can be found in the Appendices. The editors are greatly indebted to Juliet Weirsema, who was responsible for a large fraction of the planning and preparation for the meeting. We also wish to thank Emma Bakes, Max Bernstein, Kin-Wing Chan, Jason Dworkin, Peter Jenniskens, Michael Kaufman, David Lesberg, and Robert Walker who served on the Local Organizing Committee in a variety of important capacities. Finally, we wish to thank Sue Hertlein and Rho Christensen for their invaluable assistance with the preparation and production of these proceedings.

The Workshop and these proceedings were supported by a grant from NASA through the Astronomical Search for Origins program.

Executive Summary
Exozodiacal Dust Workshop
October 23-25, 1997

- 1) The amount of dust in exozodiacal systems must be measured. It cannot be predicted with our present knowledge.

Direct measurement at appropriate scales (e.g., for G stars, about 0.1 arcsec = 1 AU [Astronomical Unit] at 10 parsecs [pc]) is necessary to evaluate the amount of warm dust around nearby stars. We do not have the understanding at present to allow theoretical prediction of the amount of dust at terrestrial temperatures in a given planetary system even if it is known to contain a cold ("Vega") dust disk and/or planets. The density of the "smooth" component of an exozodiacal dust cloud depends critically on at least:

- the unique characteristics of that system's formation (e.g. total mass in comets versus asteroids);
- the specific masses and locations of major planets that control grain orbits;
- planets' continual and chaotic perturbation of dust parent bodies into collisions or ejection from the system; and
- the recent history of significant (random) asteroid collisions and large comet passages.

Dust density may also depend substantially on properties of the central star such as wind and magnetic field strengths. However, there is no present theoretical reason to suppose that the dust density in our system is either unusually low or high relative to that around other normal solar-type stars.

- 2) The power spectrum of dust density variations in an exozodiacal cloud may be modelable if the average level is known.

If the general level of the smooth component of an exozodiacal cloud is known or assumed it may be possible to model the scale and amplitude of density variations based on locations and sizes of planets and grain drift rates. However, comprehensive models for the dust dynamics in our solar system are only now being created and are not yet adequate to predict the situation in other systems, especially at sub-AU scales. Unfortunately, these scales are critical to the design of the Terrestrial Planet Finder (TPF) interferometer. For example, it is not known how the amplitude of cloud irregularities will depend on the overall density of the smooth cloud. If the cloud density is high, collisions could overcome Poynting-Robertson drag and erase corrugations, but this depends on unknowns such as characteristic grain size (which determines Poynting-Robertson drift rate) that may vary substantially from system to system.

It is probable that exozodiacal spatial variations are not "stochastic" nor characterizable by a "checkerboard" that extends across the entire system. In the local zodiacal cloud, it is estimated that the level of such variations is quite low, $\ll 0.5\%$. The known larger non-uniformities in our system such as wakes, rings, and warps are closely associated with planets. However, a system with large planetary masses in eccentric orbits such as 16 Cyg B could send asymmetries, e.g. spiral density waves, propagating far across the cloud.

On the other hand, because the dominant irregularities and asymmetries in our system's dust cloud are known to be (and around Beta Pic are hypothesized to be) caused by planets, detecting exozodiacal density variations may help locate and identify planets and infer their masses.

Substantial work is waiting to be performed in:

- acquiring requisite observations of our solar system;
- producing a comprehensive model of our dust dynamics; then
- generalizing it to other systems with different primary stars and different planetary configurations.

3) The infrared (IR) background level at 5 AU in our system is not well known.

While there is some information from Pioneer, Voyager, Ulysses, and Galileo about the dust density beyond 3 AU, there are not enough data about numbers of grains in the 10- to 100-micron size range that dominate the local background. Also, dust at 5 AU may include a substantial component of small, relatively hot Interstellar Medium (ISM) grains which do not penetrate inward of Jupiter; their higher temperatures could partly offset their lower emissivity at 10 microns. Thus, although it is likely that the local background is much lower at 5 AU than at 1 AU, we do not know enough to locate the TPF with complete confidence. This issue is sufficiently important to warrant advocating alterations in the plans and instrumentation on some upcoming space missions (see below) and encouraging modeling of the outer part of the zodiacal cloud.

4) One or more surveys for exozodiacal dust are needed before TPF.

Surveys using IR interferometry and/or sub-millimeter interferometry and/or optical polarimetric coronagraphy are needed to produce a census of dust density in habitable zones around nearby stars. This is a very necessary step before making decisions on TPF design and location. The optimum aperture size, baseline, and orbit location for TPF depend on both the expected surface brightness of exozodiacal systems and the background intensity in our own system.

5) Comparison of the sensitivity of possible exozodiacal survey instruments is needed.

Since it is vital to know which facilities will be able to detect 100- vs. 10- vs. 1-zodi clouds, it would be useful to convene an outside or non-advocate review of the

various ground-based IR and sub-millimeter interferometers and a possible coronagraphic capability for WF3 (see below) on the Hubble Space Telescope (HST), to independently examine and compare the expected sensitivities, resolutions, and other important parameters. One important outcome of such a study would be the determination of how these facilities can be used together to maximize our knowledge of exozodiacal dust.

SPECIFIC RECOMMENDATIONS

The recommendations from the Ames Exozodiacal Dust Workshop can be summarized as arguing for the establishment of a national science program to provide a solid understanding and characterization of exozodiacal and zodiacal dust emission and of the potential TPF target stars.

- There should be a program of observations that make use of available or planned facilities such as the Keck Interferometer, Large Binocular Telescope (LBT), Space Infrared Telescope Facility (SIRTF), Stratospheric Observatory for Infrared Astronomy (SOFIA), etc., to directly measure the exozodiacal emission around nearby stars. A present estimate is that a TPF interferometer resembling the present baseline designs would have degraded sensitivity to earth-like planets in systems with exozodiacal dust densities above about 10x that in our system. Systems with less dust than that become primary TPF targets. (These limits, however, will depend on the actual levels of spatial fluctuations in the exozodiacal dust clouds.)

Therefore, an attempt should be made to measure the fluctuation power spectrum in the brighter dust systems down to 0.1 AU-resolution, and then extend these results to fainter systems by modeling. Observations with the Keck Interferometer will be particularly valuable in this area.

- There should be a parallel program directed at collating what is known about all the normal stars in the solar neighborhood and at promoting the filling in and extension of that database so that target selection criteria other than exozodiacal emission strength can be understood.
- Finally, our theoretical understanding of the sources, sinks, dynamics, and evolution of our own zodiacal cloud needs to be substantially increased before we can interpret exozodiacal observations in comparison with our solar system.

These three broad programs of scientific inquiry are intrinsically interesting and should be pursued no matter what techniques and instruments are finally used to look for terrestrial planets. Support for these programs will be crucial to success in finding extrasolar terrestrial planets. At the least, support should take the form of a substantial augmentation to the existing "Origin of Solar Systems" grants program, thereby allowing a significant number of new grants, directed toward modeling of dust clouds in planetary systems.

ELABORATION OF THE THREE SCIENTIFIC PROGRAMS

- Exozodiacal surveys

A combination of: a) SIRTf detecting cold dust; b) SOFIA and the Millimeter Array (MMA) (if available early enough to influence TPF design) mapping the nearest dusty systems such as Beta Pic and Vega; c) ground-based IR interferometers plus HST polarimetric coronagraph detecting close-in dust and resolving system inclinations; d) continued radiometric and astrometric planet searches; and e) advances in theoretical models of these observations should provide the necessary understanding of exozodiacal dust clouds to ensure that TPF is designed to maximize the probability of successful detection of Earth-sized planets. Not incidentally, we would also acquire deep understanding of the formation and nature of planetary systems.

- The Keck's role in searching for planets around stars in the solar neighborhood is critical for the success of the overall program, but the Keck Interferometer is also important in understanding and predicting spatial fluctuations in the exozodiacal clouds due to the presence of planets and/or stochastic noise. Therefore, observations of the exozodiacal dust with the Keck Interferometer should be pursued. If the Large Binocular Telescope (LBT) can produce a convincing plan to reach sensitivities of 10-zodi or better with resolution of 0.1 arcsec (1 AU for systems at 10 pc), then observations with the LBT will be critical for determining the average brightness level of warm dust and, again, such observations should be vigorously pursued as part of the program to understand the exozodiacal background.
- NASA is now studying a coronagraphic capability as part of an imager (WF3) that could be installed on HST in 2002. This instrument should have the capability to detect 100-zodi clouds and resolve their orientation around nearby stars, with polarimetric capability to enhance the prominence of scattering at target systems. This instrument may reach as low as 10-zodi clouds. It may also be able to image Uranus-type planets, difficult to detect indirectly due to their long orbit periods. If WF3 with a coronagraph can reach the appropriate sensitivity level to detect clouds down to 10-zodi or below, then this instrument's possible role as a near-term exozodiacal and planetary survey facility, which complements infrared and radiometric/astrometric schemes, should be strongly considered.
- If it can be ready in time, it is important that the plans for the MMA include early-on 350 micron (shortest wavelength, finest resolution) receivers. Receivers at this wavelength would substantially increase MMA's sensitivity to warm dust, therefore making MMA an important facility in a multi-pronged approach to determining the characteristics of exozodiacal dust emission around nearby stars.
- Addition of coronagraphic capability and increased emphasis on exozodiacal dust and planetary searches within the Next Generation Space Telescope

(NGST) project should be considered as a parallel effort that will support (but not necessarily precede) TPF.

- If a combination of existing telescopes can detect systems at or below the 10-zodi level from the ground, then there is no clear need for a dedicated "Exozodiacal Mapper" mission to measure the exozodiacal levels for TPF.

- Stellar Database

This program would be aimed at comprehensive observational and theoretical understanding of the 1000 nearest stars in terms of their ages, metallicities, stellar companions, planetary companions, precise mid-IR spectral energy distributions (SEDs), wind and activity levels, galactic/extragalactic background confusion, and, to the extent possible, accurate characterization of the exozodiacal dust around the stars.

- The characteristics of the nearest stars should be known in much more depth than at present, and this should not be limited just to spectral classes F, G, and K. A careful calibration of stellar photospheric SEDs in the mid-IR via observations and atmospheric models would substantially increase SIRTf's sensitivity to optically thin emission from dust in the majority of cases where SIRTf will be unable to spatially resolve the dust cloud. The surroundings and backgrounds of these stars should be examined in detail to eliminate systems in which bright close companions or background objects would reduce interferometric sensitivity. The result of thorough understanding of these nearest neighbors should be a straw-man target list awaiting results of exozodiacal dust surveys for further culling.
- Comprehensive information on the 1000 nearest stars and a subset draft TPF target list should be maintained as a data base by NASA. Presently there are several similar lists in the astronomical community (e.g. the Search for Extraterrestrial Intelligence [SETI] target list) but a master list with all salient data is critical to properly designing TPF and could also guide the stellar community in focusing on what more needs to be known about these stars.

- Zodiacal cloud: Comprehensive understanding

Observations and modeling of our zodiacal cloud and of circumstellar dust systems should result in: a) an ability to predict the sub-AU structure in an exozodiacal system given overall dust density and planetary arrangement, using our system as a check; and b) understanding dust in terms of the origin and evolution of planetary systems (termed a "Theory of Everything" at the workshop).

- Models of dust dynamics could be used in conjunction with models of star and planet formation to explore the full range of planetary system configurations and their resulting dust cloud morphologies and densities.

- There is a need for a TPF "site survey" out to 5 AU to find the true zodiacal background emission level versus heliocentric radius. This may be accomplished by measures such as:
 - * turning on the Cassini camera and dust collector during cruise;
 - * scanning the STARDUST camera along the ecliptic to measure dust scattered light while at its aphelion distance of 2.7 AU (and make a census of small asteroids as dust parent bodies); and
 - * adding shutters or blank filters for zero level checks in the STARDUST and Pluto Express cameras.

Appropriateness of such measures and sensitivity to 10-100 micron-sized dust at expected densities need to be checked. (N.B.: Substantial reduction in the STARDUST camera dark current is apparently possible by a small modification to the instrument; we urge NASA to consider asking the Principal Investigators and Lockheed Martin to make these changes.)

- There is no clear need for a "Local Zodiacal Cloud Mapper," especially if the required site survey information can be acquired through augmentations of planned missions.

Invited Talks and Related Discussions:
Science

