A Search for Substellar Companions of the Debris Disk Star ε Eridani with the Spitzer Space Telescope

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ε Eridani (HD=22049, d=32pc) is one of the "Fabulous Four" debris disk stars discovered by IRAS (together with Vega, Fomalhaut and β Pictoris). Observations with the Multiband Imaging Photometer (MIPS) and the InfraRed Spectrometer (IRS) of the Spitzer Space Telescope have confirmed the presence of the disk, and provided evidences for asymmetries in the disk structure that may be induced by the gravitational perturbation of substellar companions. With an age of 730 Myr (Song et al. 2000), ε Eridani represents a particularly interesting object for studying the evolution of debris disks and their associated exoplanetary companions.

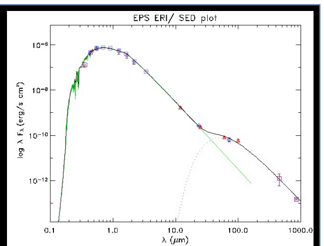
We present here a search for substellar companions of ε Eridani which is being carried on with the InfraRed Array Camera (IRAC) of Spitzer. The optical quality and high dynamic range of the camera is specially suited to detect faint companions around bright stars, and its four bandpasses at 3.6. 4.5, 5.8 and 8.0 μm are ideal for the search of substellar objects by detecting their molecular spectral features.

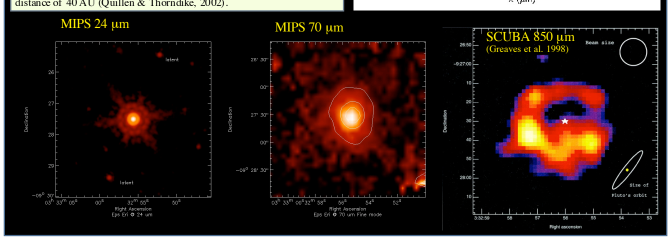
We discuss the special techniques we have developed to reduce the effects of the bright central star which is the main limiting factor in allowing the detection of faint companions, and the sensitivity limits that our techniques can reach.

MIPS images of ε Eridani at 24 and 70 μm

The ε Eridani SED shows a strong infrared excess generated by its debris disk. To measure this excess and image the disk at far-IR wavelengths, we have observed ε Eridani with the MIPS instrument onboard the Spitzer space telescope. At 24 μm the disk is unresolved, but we did measure a 12% excess above the expected photospheric flux. The disk is instead resolved at 70 μm, with a size R~34" (3σ detection level), elongated in the N-S direction. The MIPS 70 μm flux is ~1.5 Jy (the expected photospheric flux is ~0.2 Jy).

The S/N of the current MIPS images does not allow the detection of the clumped structures imaged by SCUBA at 850 μm (Greaves et al. 1998). The submillimeter data indicates that the disk may have an asymmetric ring structure, with a central cavity of the size of ~65 AU. Dynamic models of the system suggest that the cavity and asymmetries may be the consequence of an unseen planetary companion orbiting the star at the distance of 40 AU (Quillen & Thorndike, 2002).





IRAC search for substellar companions

The recent discovery of a planet orbiting ε Eridani at the close distance of 3.4 AU (Hatzes et al. 2000) shows that this star is indeed forming planets. Attempts to detect other substellar companions in this system, based on methods other than radial velocity and eclipse measurements (which are limited to massive planets in proximity of the star), have however given negative results (Machintosh et al. 2003, Proffitt et al. 2004). The main difficulty faced by these searches, aimed to directly detect the luminous emission from the companions in the near-IR and optical, is the inability to suppress the light coming from the central star, many order of magnitude stronger than the luminosity of the companions. Mid-IR wavelengths, where the emission from the companions peaks, offer a better chance for the detection.

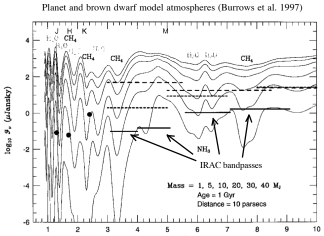
The InfraRed Array Camera (IRAC) of Spitzer is particularly suited for this task, thanks to its optical stability, high dynamic range and the choice if its photometric system. Its bandpasses at 3.6, 5.8 and 8.0 μm are located in spectral region affected by heavy methane, ammonia and CO absorption bands, while its 4.5 μm band rests in a region relatively free of molecular absorption.

Colors based on IRAC photometric system have proven extremely effective in the detection of substellar objects, and in discriminating between stars and extragalactic sources (see Patten et al. #11.10, this conference).

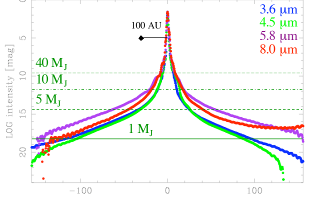
Even at IRAC wavelengths, however, the brightness of ε Eridani is formidable. The figure below shows the profiles, in logarithmic units, of the IRAC Point Spread Functions (PSFs) scaled to the ε Eridani flux. The profile is extracted at a position angle of 45º, in order to avoid the diffraction spikes due to the secondary mirror support, and other PSF artifacts. The brightness of profiles extracted along the spikes would be increased by ~1-2 magnitudes.

The thin green lines show the peak brightness of substellar companions derived from Burrows et al. (1997) models of planets and brown dwarfs with 1, 5, 10 and 40 M_J and 1 Gyr of age, at 3.6 μm. Note that within the first 100 AU from the star, planets with mass of 5 M_J or less are always fainter than the IRAC PSF extended tails. Even with IRAC, removal of the PSF is necessary to allow detection of planets around ε Eridani.

Planet and brown dwarf model atmospheres (Burrows et al. 1997)



IRAC PSF models rescaled to ε Eridani flux
compared to planets/brown dwarfs predicted brightness

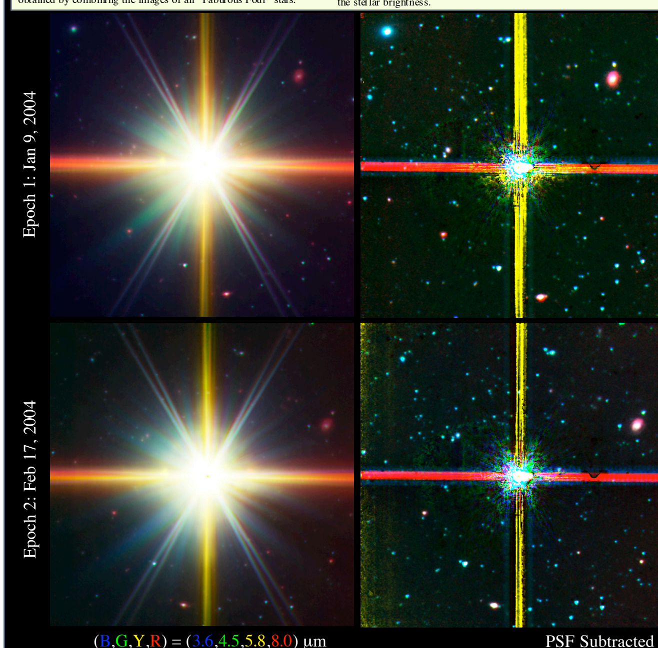


PSF subtraction techniques

The IRAC observations of the "Fabulous Four" stars have been designed with the aim to optimize the PSF removal. For this reason each star has been observed in two separate epochs with a different roll angle of the telescope. By subtracting one image from the other, all the PSF features are removed, leaving behind only the point sources in the field that has rotated between the two observations. This technique however suffers from severe limitations in the case of crowded stellar fields (as the one around ε Eridani), because the subtracted image leaves behind a "negative" version of the rotated field, that can alias the stars in the "positive" image. For this reason we have developed a complementary technique based on a model PSF obtained by combining the images of all "Fabulous Four" stars.

Given the brightness of the "Fabulous Four" stars, the central part of the reconstructed PSF is heavily saturated. To solve this problem, and make possible to use the reconstructed PSFs also for less saturated objects, we have modeled the psf core by using a set of unsaturated reference stars. The final PSF thus traces the point source emission from its peak to its tails, falling off the border of the IRAC arrays, for a total of 7 orders of magnitudes in brightness.

The figure below shows the IRAC four color images of ε Eridani observed in January and February 2004 before (left) and after (right) the PSF subtraction. The yellow and red cross is the subtraction residual of electronic artifacts in the IRAC images, that cannot be removed properly with this technique as they do not scale linearly with the stellar brightness.



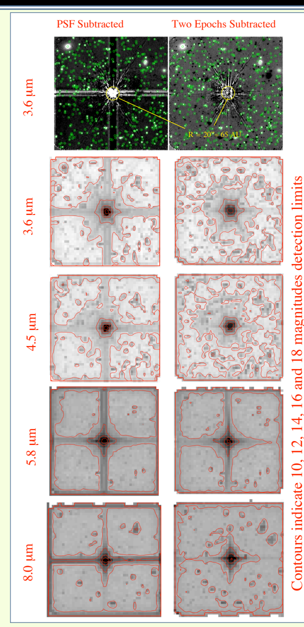
Source detection

The two panels on top show the 3.6 μm IRAC images of ε Eridani (first epoch) after subtraction with the model PSF (left), or subtraction with the second epoch (right). The green circles show the sources detected in the field (over 400) for which a 3.6 μm flux can be derived. A similar number of sources are also detected at 4.5 μm, while the detection rate diminishes at 5.8 and 8.0 μm because of the higher noise characteristic of the long wavelength channels. The yellow circle indicates a radius of 20" from the star, equivalent to 65 AU at the ε Eridani distance. Within that radius, saturation prevents the detection of any source. Outside this circle most of the flux of the central star is removed, with the exception of a "cross" due to the electronic artifacts in the IRAC PSF. These artifacts are removed in the two epochs subtracted image, which is however showing a larger noise because of the source aliasing in the "negative" frame.

Sensitivity maps

The ability of these techniques to remove the central star light and allow the detection of fainter sources is shown in the maps at the right. The greyscale images show the residual noise in the PSF and second-epoch-subtracted images. The noise is maximum at the center where the source is saturated, and gradually decreases towards the images border, tracing the diffraction spikes and the other PSF artifacts where the PSF subtraction is less good.

The red contours show the 5σ detection limits, in magnitudes, for companions in the subtracted images. From the center outwards, the contours enclose the areas where the minimum magnitude of detectable sources is 10, 12, 14, 16, and 18 respectively. For example, in the light colored areas 2 arcmin away from the star, the residual noise in the 3.6 and 4.5 μm maps is low enough to allow a solid detection of sources fainter than 18th magnitude. Planets with mass of 5 M_J or less (having a magnitude of ~14 according to the models) can only be detected outside a radius of ~35" (110 AU from the star). At 5.8 and 8.0 μm the noise level is in general higher by almost two magnitudes, due to the larger flux contained in the tails of the PSF, and because of the less sensitivity of the IRAC array at those two wavelengths.



Work in progress

We are currently analyzing the photometry of the more than 400 sources detected in the PSF subtracted frames. We will present the results of our search in a forthcoming paper which is currently in progress.

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