# SPACE INTERFEROMETRY MISSION

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**Abstract**

The Space Interferometry Mission (SIM) is NASA's first space science interferometer, and will enable fundamental new discoveries in both Galactic and extra-galactic astronomy, including cosmic distance scale. It will also address questions related to the origins and prevalence of planetary systems. SIM is designed with a 10m baseline, providing high-throughput 4 pas global astrometry and synthesis imaging, in the visible at a resolution of 10 milliarcsec. It demonstrates several key technologies, including coronagraphic-type 10" extinction nulling of a central bright source, needed for future missions in NASA's Origins Program, such as the Next Generation Space Telescope (NGST) and Terrestrial Planet Finder ('1'1'1').

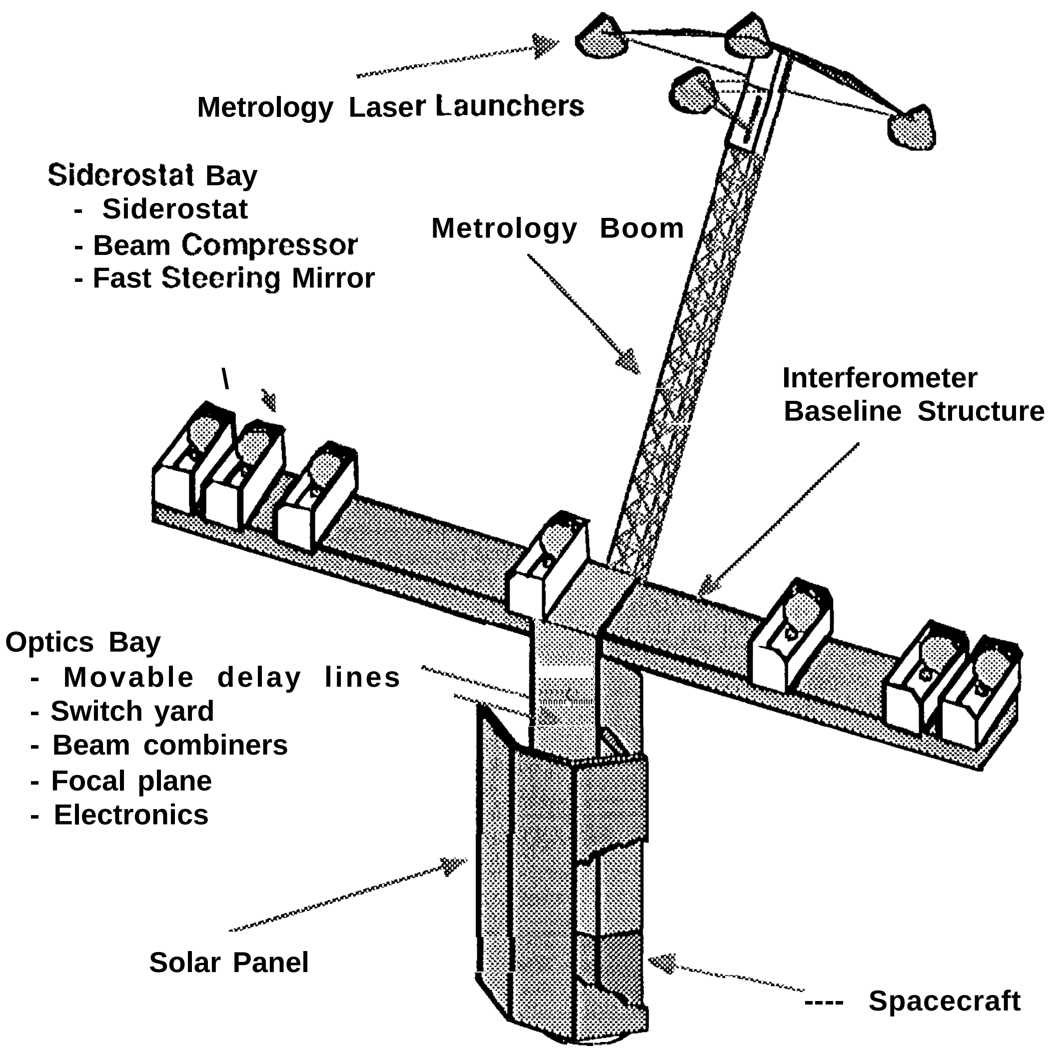


FIGURE 1: Overview of the S1 M spacecraft

## IN'I'ROD11CTION

S1 M is a 10 meter baseline visible interferometer capable of global astrometric measurements with 4 µas (2 x $10^{-11}$ rad) accuracy and narrow-angle astrometric measurements 011 the order Of 1 pas (1'able 1), It will produce. a wealth of new astronomical data and serve as a technology pathfinder for a line Of future astrophysics missions. The baseline concept for S1 M is derived from the Orbiting Stellar Interferometer (OSI) concept developed at the Jet Propulsion Laboratory (Rayman 1992). The SIM architecture (Figure 1) represents a paradigm shift from the era of rigid monolithic telescopes. SIM embraces the new paradigm of active optics distributed acres a lightweight flexible structure which maximizes resolution pcr unit mass carried into orbit. This is a necessary step forward for future low-cost large-aperture space astrophysics missions, Table 1 summarizes the principal instrument and mission parameters. Figure 2 shows the expected wide-angle astrometric accuracy as a function of stellar magnitude and integration time.

TABLE 1. SIM 1 nstrument and Mission Parameters

| | |
|---|---|
| **Instrument** | |
| Baseline | 10 meters |
| Wavelength Range | 400 -- 1000 nm |
| No. Siderostats | 7 |
| Aperture Diameter | 0.30 meters |
| Astrometric FOV | 10° x 10° |
| Imaging FOV | 2.4 x 0.4 arcsec |
| Detector | Si CCD and Al']) |
| **Missirm/blight System** | |
| Orbit | 900 km Sill}-symh. |
| Orbit Period | 103 min |
| Launch Vehicle | Delta-II 7920 |
| Mass | 1800 kg (79% margin) |
| Power | 1030 W (63% margin) |
| Lifetime | 5 years |
| **Science Performance** | |
| Astrometry (wide-angle) | 4 µas on 20 mag in 10 III-S |
| Astrometry (narrow-angle) | 1 µas on 15 mag in 3 hrs |
| imaging Resolution | 10111:!s @ 500 nm |
| Imaging Sensitivity | |
| Point Source | 25 mag in 1 hr |
| Extended Source | 20 mag/pix·1'111 hr |
| Nulling | $10^{-4}$ |

SIM leverages on a number of past, current and upcoming activit ics to significantly reduce mission cost a ad risk, It benefits from the rich history of ground-based interferometers and associated JPL personnel, ranging from the Mark I -- Mark III systems at Mt, Wilson, to the currently operating Palomar Testbed Interferometer, and envisioned Keck Interferometer. These programs provided some of the first interferometry technology demonstrations using starlight. The Interferometer Technology Program (1'1'}') at JPL focuses the ground-based on technologies needed for space. This broad program encompasses components, subsystems, and integrated systems that validate interferometer operations. Critical interferometer components such as siderostats, delay lines, and lasers are currently in advanced development to meet the environmental rigors of space. Metrology gauges with accuracies at the picometer level that arc necessary for S1 M arc currently being demonstrated in the laboratory. Ground testbeds, like the Micro-Precision Interferometer (MPI) testbed, are demonstrating end-to-end operation of an interferometer on a large flexible, flight-like structure. Advances in the development of modeling tools arc enabling high-fidelity prediction of S1 M's pert'ormaacc in space.

In addition to global and narmw-angle astrometry, SIM will also perform synthesis imaging with 10-milliarcsecond resolution. By combining different siderostat pair-s, and rotating the spacecraft about the line of sight, the instrument samples the Fourier transform '(u, v)' plane, from which the image brightness distribution can be deduced. Figure 3 shows the. expected imaging sensitivity for various object sizes (in units of 10 milliarcsecond pixels.

~'able 2 summarizes the astrometric program which SIM will undertake; specific targets or target classes are identified. Some principal science objectives include:

- Calibration of stellar and "standard candle" luminosities used in cosmic distance scale and globular cluster measurements
- Precise studies of galactic dynamics including rotation curves a ad halo object motions
- Searching for planets down to an Earth mass
- Measuring the apparent astrometric motion in gravitational microlensing events
- 10 milliarcsec resolution synthesis imaging of circumstellar disks around young stellar objects (>'SOS)
- Imaging the narrow-line regions of active galactic nuclei (AGN)
- Demonstrating nulling by imaging the dust around β Pictoris 10 within -0.1 All (1 .S. 10'°m) of the star, 10 search for gaps or structure that may be caused by the presence of planets

TABLE 2. SIM Astrometric Program Highlights

| Science Topic | Objective | Target Description | Magnitude Range | Comments |
|---|---|---|---|---|
| Dark Companions | Astrometric Detections of Planets, BD, WD, MACHO Candidates | Nearby Stars, LMC, SMC, and Bulge Field Stars, Possible MACHO Companions | Local: 2 --12 Bulge: 15-- 18 LMC: 18 - 22 | Detect Gas Giants; BD and WD companions, MACHO Astrometric Effects |
| Luminosity Calibration | Calibrate/Constrain Astrophysical Models | MS Stars, Cepheids, RR Lyrae, PN, Nova/CV | MS: 4 -- 12 Cep: 7.s -- ] 1 PN: 10--18 | Calibrate MS Stars, Standard Candles, End-States (O (1%) range error) |
| Binary Systems | Mass Distributions of Binary Constituents | MS Binaries, CV (White Dwarfs), XRB (Neutron Stars, Black Holes) | MS: 6 -- 12 CV: 12 -- 18 | Unequivocal Mass Distributions |
| Globular Clusters | Calibrate Cluster Distances/Ages, Cluster Dynamics | Globular Clusters (47 Tuc, ω Cen, M15, etc.) | 6-- ]4 | Cluster Age Determination, Dynamics (Crowded Field Operation) |
| Galactic Structure | Rotation Curve Spiral Arm Halo Kinematics | Early Main Sequence@ 2--20 kpc, Halo K Giants | 10 -- 18 | Spiral Arm Densities, Dark Matter Distribution |
| AGN | BLR Fluctuations, '1'l[lllS\'else Peculiar Velocities, AGN Microlensing | AGN Within 100 Mpc | 13 -- 20 | Correlate Astrometric and Photometric Fluctuations, Large- |

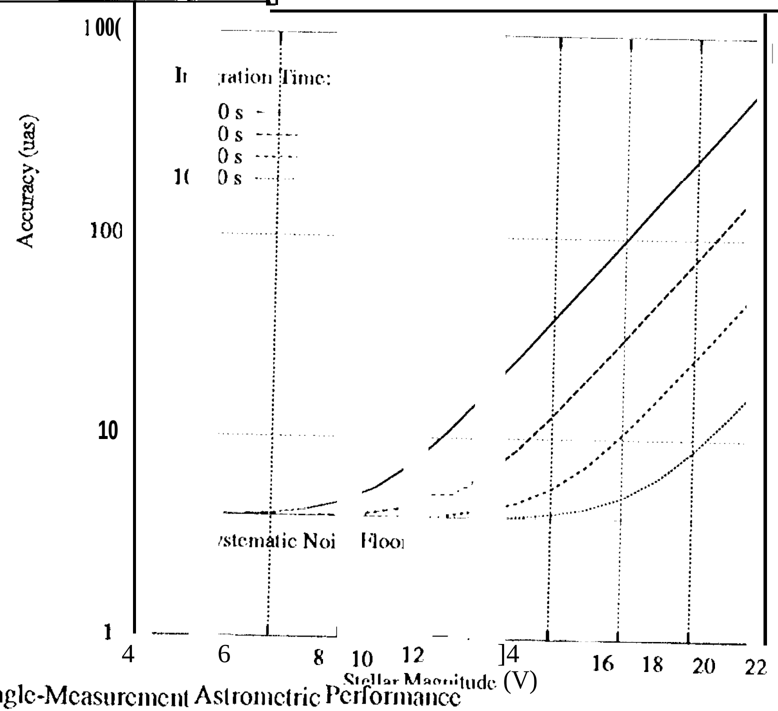


FIGURE 2. S1 M Single-Measurement Astrometric Performance

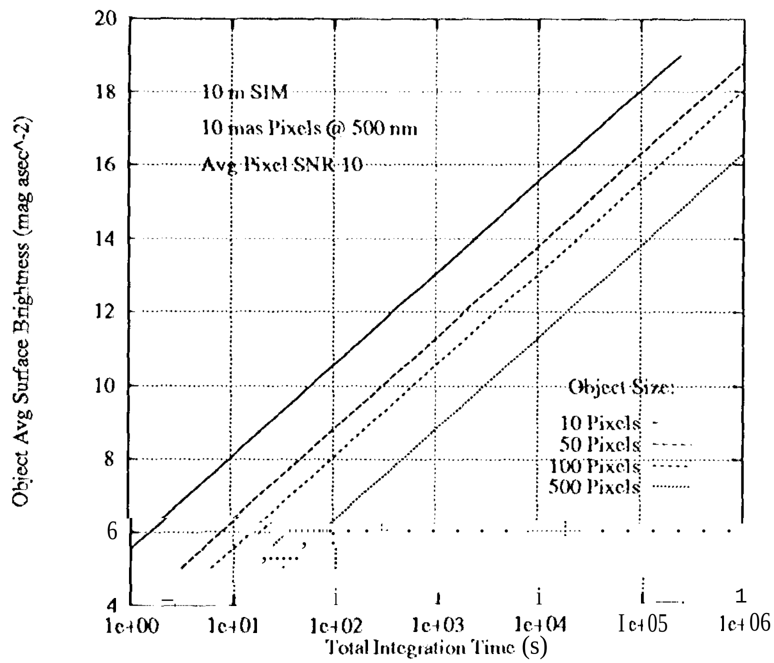


FIGURE 3. SIM Rotational Synthesis imaging, Sensitivity

SIM ORIGINS SCIENCE

The science program for SIM is very broad, and involves many areas of astrophysics. It contributes 10 the scientific goals of NASA's Origins Program in several fundamental ways, with regard to the study of extrasolar planetary systems, and in establishing the cosmic distance scale. in this paper we focus on the Origins science topics addressed by SIM.

**Planets of Nearby Stars**

*Which nearby stars have planets? What are those planets like? How pervasive are planets and planetary systems around nearby stars? What statistical information can be gained about the formation of these systems, and what can we infer about how these systems are formed?*

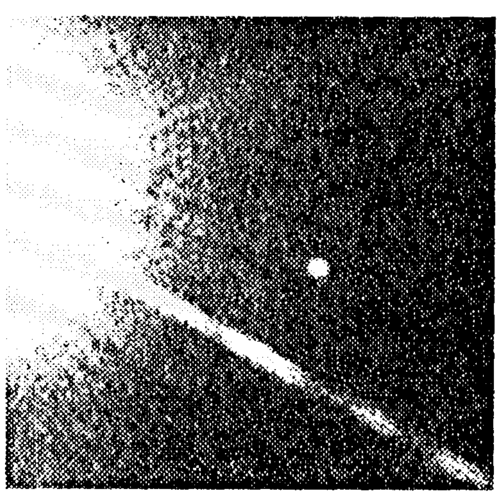

FIGURE 4. HST Image of the Brown Dwarf GL229B (Nakajima et al)

Over the last year there have been two significant developments in the nascent field of extra-solar planetary research First is the inference of companions with masses in the planetary range of 1 to 10 $M_J$, (where Jupiter mass $M_J$ = 9.6.10-"' solar masses) around the nearby stars 51 Peg (Mayor and Queloz 1995) and 70 Vir (Marcy and Butler 1996). These are the first positive results from precision radial velocity studies. Second is the direct detection of a genuine brown dwarf, the companion of the nearby star Gliese 229 (Nakajima et al. 1995). Spectroscopy (Oppenheimer et al. 1995) reveals strong methane absorption bands. Such bands are not seen in other stars, but are common to large giant planets (e.g. Jupiter).

These discover ics dispel many myths about planetary formation and brown dwarfs. Planets found by radial velocity are peculiar in all respects: the planet orbiting 51 Peg is in a 4 day orbit at about 10 solar radii, and the one around 70 Vir has an eccentricity of' 0.38. Formation of' such giant planets

TABLE 3. Potential Target Stars in an Astrometric Search for Earth-like Planets as a Function of Astrometric Accuracy (from Shao 1996).

| SIM Metrology Performance (pm) | SIM Narrow-Angle Astrometric Accuracy (mas) | Number Stellar Targets |
|---|---|---|
| 300 | 6 | 1 |
| 200 | 4 | 2 |
| 100 | 2 | 4 |
| 80 | 1.6 | 6 |
| 60 | 1.2 | 10 |
| 40 | 0.8 | 32 |
| 30 | 0.6 | 89 |
| 20 | 0,4 | 303 |
| 10 | 0.2 | 1167 |

(6 $M_J$) in such eccentric orbit is not explainable by current theory.

Our current understanding of planet formation is based on only one example, the solar system. To first order, we can divide the planets into rocky planets (e.g. Venus, Earth, Mars) and giant gas planets (e.g. Jupiter, Saturn, Neptune and Uranus). We believe that all the planets contain a rocky core which formed first by coalescence of dusty material. In the cooler (outer) regions gas accreted onto large rocky cores to form the giant planets. The extrasolar planet candidates discovered to date are not easily explained with this paradigm. To make planetary science into a comparative field we need more data, specifically a census of planetary bodies around stars in the solar neighborhood.

SIM will contribute in a unique manner to this census. Its astrometric precision coupled with high throughput enable us to search for rocky planets around the nearest few stars and intermediate-mass planets (Uranus) over the nearest 1000 stars. None of these bodies are accessible to ongoing or future radial velocity studies.

Observations are urgently needed to guide our understanding of planet formation, in particular to address the following questions:

*What is the frequency of large gas planets? What is the frequency of brown dwarf companions? What is the frequency of rocky planets? What is the mass range of planets? Is our planetary system a minimal planetary system (what is the smallest number of planets a G star can have)? Can we shed light on the genesis of the bizarre planets that have already been detected?*

A large census of all nearby stars is needed to answer these questions.

The astrometric detection of dark companions to luminous primaries is achieved by measuring the transverse reflex motion of the primary as it orbits the common center of mass of the system. Astrometric detection differs from the radial velocity technique in that the *magnitude* of the astrometric signature is independent of the orbital inclination. Two dimensional astrometric information uniquely defines the orbital inclination of the companion, and a distance uniquely defines the stellar mass, thereby uniquely defining the mass of the companion. Astrometric companion detection is done via narrow-angle astrometry, so SIM's performance in this project will be between 0.6 and 1 pas. The size of the apparent reflex motion is:

$$\Delta\theta = 6\mu as\left(\frac{R}{1AU}\right)\left(\frac{D}{1pc}\right)^{-1}\left(\frac{m}{m_e}\right)\left(\frac{M_*}{M_{sun}}\right)^{-1}$$

where R is the orbital separation, D is the distance to the system, m is the. mass of the companion and $M_*$ is the mass of the parent star. Starspots moving across the stellar disk start to become a significant problem for astrometry at 1 pas; however this difficulty be overcome by performing multi-color astrometry -- effectively solving for the astrometric error induced by the starspots (Shao 1996).

Searching for dark companions to stars nearer than 100 pc (1 pc = $3.1.10^{16}$ m), SIM with a 1 pas narrow-angle astrometric accuracy is sensitive to reflex motions of amplitude greater than 0.02 solar masses and periods shorter than twice the mission length (nominally a 5 yr mission, so companion periods shorter than 10 years). This reflex motion sensitivity corresponds to planets with masses down to 1% of Jupiter orbiting solar-mass stars, so SIM will easily detect gas giant and brown dwarf-type companions around a very large number of candidate stars -- enough to establish highly significant mass distributions. Table 3 gives an estimate of the number of accessible target stars within 25 pc for an earth-like planet search as a function of the system astrometric accuracy (as extracted from the Gliese catalog, Shao 1996). SIM's 0.6 - 1μas narrow-angle astrometric performance is capable of detecting earth-mass companions around the nearest 12 -90 stars. This program has important implications fot-the Terrestrial Planet Finder mission.

## Characterizing Brown Dwarfs

*What is the nature of the dark companions observed thus far, and surely to be discovered in the near future?*

Direct detection of the 'super'-pkrncts is of considerable interest both from the point of view of conveying excitement of this field 10 the public at large and for carrying out detailed studies of these systems. Indeed, the recent publicity afforded the direct detection and spectroscopy of the brown dwarf Gliese 229B is a testament to both these justifications. The modeling of planetary atmospheres is still in its infancy. Low temperatures result in formation of many molecules, which make the modeling difficult. This is unfortunate since detection strategies require a good knowledge of the emitted spectrum. For example, the spectrum of Gliese 229B peaks al 1 μm even though $T_{eff}$ = 900 K (Matthews et al, 1996). Furthermore the strongest spectral features in Gliese 22911's spectrum arc due 10 methane, remarkably similar to the reflected spectrum of Jupiter.

SIM's nulling capability is the only way to directly detect the majority of brown dwarfs inferred from indirect (radial velocity or astrometric perturbations) techniques. In studies of such systems, SIM and 11ST will play complementary roles -- S1 M will enable us to explore and study brown dwarf companions with orbital separations less than 1 arcsec, while HST can image systems at larger separations (see Figure 4). Using Gliese 229B as a prototype, the absolute magnitude in the range 0.8-1 μm is between 17.5 and 1 S (Nakajima et al. 1995). SIM need only achieve a contrast of 104:1 to image and measure the. flux from Gliese 2291]-like objects. It will be interesting 10 see how the spectrum of the brown dwarfs depends on effective temperature. Gliese 229B with $T_{eff}$ = 9(KI K peaks at 1 micron whereas Jupiter ($T_{eff}$ = 120 K) peaks at wavelengths longer than 10 μm (the true emitted spectrum). Thus we have a range of near'ly a factor of 10 in $T_{eff}$ over which we will be able to determine the optical spectrum of brown dwarfs al 1 % spectral resolution. S1 M can synthesize i mages of such compact objects efficiently; an image can be synthesized in roughly six hours.

## Stellar Debris Disks

*What is the nature and distribution of circumstellar material around main sequence and pre-main sequence stars? What are the implications for the formation of stars and planetary systems? Can the presence of planets be inferred from structure in these disks?*

*The Detection of Exo-Zodiacal Disks* The 1 RAS satellite revealed that many mai n-sequence stars are surrounded by disks of circumstellar dust, with stars such as Vega and β Pictoris having, up to $10^4$ more material than in our solar system. The exact distribution of the dust in these solar systems is poorly known. Optical coronagraphic measurements (Artymowicz, Burrows and Paresce 1989; Golimowski, Durrance and Clampin 1993) and thermal IR measurements (Backman, Gillett, and Witteborn 1985) have probed the central 4-20 asec of the β Pic disk, corresponding 10 a region from 75-300 AU (the distance to β Pic being roughly 15pc). The coronagraphic measurements show an R-band surface brightness of-15 mag $asec^{-2}$ at 100 AU, increasing as $R^{-2}$ closer to the star. This sut-face brightness is consistent with there being approximately 10" more material in orbit around β Pic than around the Sun, with β Pic being 10 limes brighter than the Sun. and with the β Pic disk being seem almost edge-on. The interest in the β Pic system is incr-cased by recent announcement by Burrows of distortions in the disk seen in HST imagery -- presumably due to the gravitational influence of one or more unseen concentrated bodies (Burrows 1996).

SIM can measure the total brightness of the β Pic disk and of other systems within a range of distances from the central star that is critical for Origins goals. Toward β Pie, the nulling system will measure the visible exo-zodiacal mission at distances of about 0.2 AU (as determined by the 10 m interferometer baseline and the 0.5 mm operating wavelength) to about 3.5 AU (as determined by the 0.33 m aperture of the individual telescopes). This is just the range of distances where the Terrestrial Planet Finder will be searching for planets, so that expanding our knowledge of the inner zodiacal clouds of even a few stars is very important.

Figure 5 plots the predicted 500 nm emission from the β Pic disk out 10 4 AU (top curve). The middle curve shows the same model, but for a system with 100 limes Jess circumstellar material. The bottom curve shows the SIM imaging detection limit as sc( by the leakage of the attenuated starlight from β Pic through the nulling system, with a maximum attenuation of $10^{-3}$ (due to β Pie's finite size), The β Pic disk is measurable against the attenuated starlight in less than 1000 sec. The middle curve -- representative of systems 10-- 100 times fainter than β Pic (which includes most of the sample of probable disk systems identified in the IRAS survey) should be detectable by this technique.

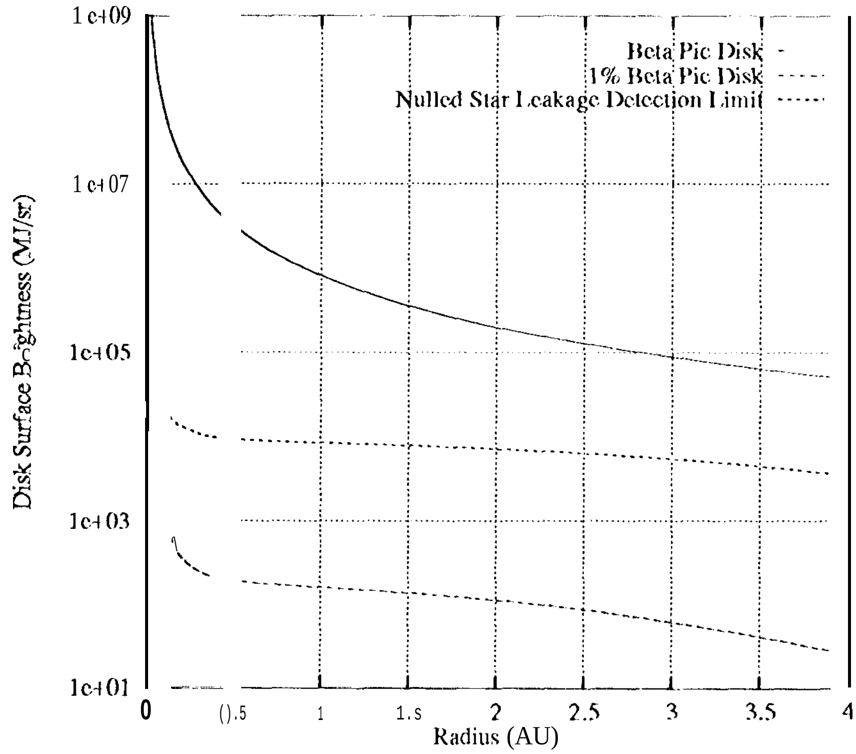


FIGURE 5: Exo-Zodical Emission Surface Brightness from β Pictoris

The minimum data that SIM will obtain arc total flux measurements of the exo-zodiacal cloud toward dozens of β Pic analogs. A secondary goal will be to derive simple imaging information by rotating the interferometer around the line of sight to the star, thereby rotating the grating function on the sky, by varying the wavelength of observation from 0.5 10 1 μm, and by varying which telescopes feed the nulling beam combiner. The combination of these techniques will allow u-v coverage sufficient to search for structures such as gaps or density enhancements due 10 possible presence of planets, in the. exo-zodiacal cloud. This experiment provides a direct test of the techniques planned for Terrestrial Planet Finder.

*Imaging YSO disks* It is a generally accepted observational fact that many young stellar objects (YSOs) -- and '1' '1'sari stars in particular -- are accompanied by optically thick circumstellar disks, Approximately 30 -- 50% of YSOs exhibit an infrared excess indicative of the reprocessing of visible radiation by these disks, and HST/WFPC2 has resolved these disks in several instances (e.g. Orion Nebula, by O'Dell and Wen 1994; Ill 130 by Stapelfeldt 1996). These disks are profoundly interesting as they are thought to be both critical to star formation and the progenitors of planetary systems. The physics of such systems is poorly understood (Bodenheimer 1995).

Koerner et al. have imaged the disks around several T Tauri stars in millimeter wave (Koerner 1993, Koerner 1995a, Koerner 1995b). In particular they find that the classical '1' Tauri star GM Auriga at a distance of 140 pc has a large circumstellar disk extending out to 1000 AU with a mass of roughly 0.1 solar masses, This same disk has been imaged with WFPC2, where the disk is observed to be inclined al 25 degrees to t he line-of-sight, a ad covers roughly 6 $asec^2$ (Stapelfeldt 1996). The prospect for a synthesized image of the region near the. central star is especially interesting because the 12 and 25 μm IRAS data on this object indicates the presence of a central clearing in the disk -- estimates of the size of the clearing arc from ().2 to 1 AU in radius. Surface photometry as close as 200" mill Iliarcsec to the central star measures V-band surface brightness from 14,5 to 17.5 $arcsec^{-2}$, sufficient for imaging with SIM even with low contrast, and a 10 milliarcsec resolution image of a small portion of the disk with a minimum SNR of 10 could be synthesized roughly 30 hours, resolving features as small as 1.4 AU. SIM's 10 milliarcsec imaging resolution and nulling capability would be sufficient to image the larger (1 AU radius) clearing size.

## The Cepheid Distance Scale

*Q: What is the cosmic distance scale? What can be done to improve the accuracy of the Cepheid-based crucial first 'rung' of the distance ladder?*

Establishing the distance scale is a fundamental problem in cosmology. Current estimates of the Hubble parameter are in the range of 45-90 km $s^{-1}Mpc^{-1}$, large enough to strongly affect models for the Universe's evolution and force some rather uncomfortable potential discrepancies with inferred globular cluster ages (Chaboyer 1995; Chaboyer et al, 1996). Of crucial importance in setting the distance scale is an accurate calibration of Cepheid luminosities. This problem is so important that its solution is one of the primary science goals of the Hubble Space Telescope. The final results of the HST determination of the Hubble constant via Cepheids is expected to have an uncertainty of 10% (Kennicutt 1995).

SIM will improve this situation in several important ways: measuring precise parallaxes of Galactic Cepheids, improving extinction estimates for the nearest Cepheids, and directly determining the distance to M31 and its Cepheid population. By directly measuring the distances to galactic Cepheids by trigonometric parallax as accurately as 0.5%, their luminosities will become known to 1%. This astrometric program is quite simple, involving 10 measurements of 50 stars within 5 kpc. They are all brighter than V-12, so the time requirements are modest, about 2 days. This study will give high-fidelity information on the period-luminosity relation for Galactic Cepheids required to make a calibration to Cepheids in distant galaxies.

Once astrometric distances are available at such precision, extinction along the line of sight to Cepheids becomes the dominant source of luminosity error in the P-L diagram. SIM can address this problem as well. If one simultaneously determines the flux, spectrum, and subtended solid angle to a high accuracy, then the extinction is readily found. Operating in nulling mode, the angular diameters (expected to be a few milliarcsec) of the brightest and closest Cepheids can be determined to 0.5-1%. This experiment operates by measuring the photometry while scanning the null over the stellar position. Since the objects are bright ($M_V \sim -5$, $m_V \sim 5$ at 1 kpc), the time required is short, of order 1 hour per target. Each star should be observed at a number of points in its period so the time-independent extinction signal can be deconvolved from the time-varying spectral and flux information. Only a handful of Cepheids are close enough for SIM to observe in this fashion. This experiment requires 5 stars x 1 hour x 10 visits = 2 days of observing time.

*Rotational Parallax Distances* SIM can measure the distances to nearby spiral galaxies *directly*, using rotational parallax, giving an extragalactic calibration of the Cepheid distance scale. Consider the proper motion of a star in M31 as it orbits the center of that galaxy. We know via HI observations the velocity field of M31 to high accuracy (the stellar velocity field would be more direct since there can be relative streaming, but this can be done via a ground-based observing). At a galactocentric radius of 5 kpc the velocity field is circular with an amplitude of 200 km $s^{-1}$. At a distance to M31 of 0.8 Mpc, SIM can measure the associated proper motion with 3% errors for a single target. This error is smaller than the expected velocity dispersion of Population-I stars in M31's disk, so performing this measurement on ~25 bright stars will enable a distance measurement to the 1% level. As long as stars are chosen from portions of the galaxy where the rotation curve is flat, the unknown vertical distance of the star above or below the disk is not important. The brightest stars in M31 are V~16 -- 17, so this experiment requires about 10 minutes per target per visit, amounting to about 2 days of observation.

## CONCLUSIONS

The Space Interferometry Mission will make many important astronomical contributions during its 5-year mission. Among the SIM contributions central to the Origins theme will be a wealth of data concerning the pervasiveness of planetary systems around nearby stars, mass statistics of these planets, high-resolution morphological information on emerging planetary systems, and a critical calibration of the Cepheid-based distance ladder.

### Acknowledgments

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