EXCEPTIONAL STARS
ORIGINS, COMPANIONS, MASSES AND PLANETS

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1. Executive Summary

As SIM Interdisciplinary Scientist, we propose to study the formation, nature and planetary companions of the exotic endpoints of stellar evolution. As part of this program, we will contribute to the mission:

- a tie of the SIM frame to the ecliptic (Solar System ephemeris) frame with better than 20μas precision.
- a study of the problem of amplitude calibration for SIM, and the requirements for precision work on binary stars unresolved by the individual SIM apertures.
- a study of the effects of distant companions to grid stars, in particular on SIM's sensitivity to long-period binaries, and suggestions for avoiding these effects.

The science we propose begins with stars evolving from asymptotic branch giants into white dwarfs. We will determine the parallax and orbital inclination of several iron-deficient post-AGB stars, whose peculiar abundances and infrared excesses are evidence that they are accreting gas depleted of dust from a circumbinary disk. Measurement of the orbital inclination, companion mass and parallax will provide critical constraints. One of these stars is a prime candidate for trying nulling observations, which should reveal light reflected from both the circumbinary *and* Roche disks. The circumbinary disks seem favorable sites for planet formation.

Next, we will search for planets around white dwarfs, both survivors from the main-sequence stage, and ones newly formed from the circumbinary disks of post-AGB binaries or in white dwarf mergers.

Moving up in mass, we will measure the orbital reflex of OB/Be companions to pulsars, determine natal kicks and pre-supernova orbits, and expand the sample of well-determined neutron star masses. We will obtain the parallax of a transient X-ray binary, whose quiescent emission may be thermal emission from the neutron star, aiming for precise measurement of the neutron star radius.

Neutron stars receive large kicks at birth. OB companions unbound by this kick become runaway OB stars. Yet some OB stars appear so high above the galactic plane they could not have gotten there in their lifetime. Some may be misidentified post-AGB stars, some may have formed 10kpc above the Galactic plane; we will find their true nature from their proper motion and parallax (or limit thereto).

A few neutron stars whose kicks are suitably oriented can remain in low-mass X-ray binaries. Proper motion and parallax measurements, combined with radial velocity, fix their true space velocities, and thus test the scenarios for their formation.

Finally, black holes. We will measure the reflex motions of the companion of what appear to be the most massive stellar black holes. The visual orbits will determine natal kicks, and test the assumptions underlying mass estimates made from the radial velocity curves, projected rotation, and ellipsoidal variations. In addition, we will attempt to observe the visual orbit of SS 433, *as well as* the proper motion of the emission line clumps in its relativistic jets.

The proposer, Kulkarni is a versatile scientist with a long heritage in the SIM project and experience in radio, infrared, optical and X-ray observations of compact objects. In support of his proposed effort, Kulkarni has assembled a small group of collaborators. Vasisht (CoI), is an expert in pulsars and optical interferometry. Van Kerkwijk, expert in observations of compact objects. Phinney, a versatile Caltech theorist and expert in compact objects and stellar evolution. Hansen, expert in the theory of white dwarfs, planet formation and dynamics.

The proposed budget (§10) is largely salary for the PI.

2. Planets around White Dwarfs: Survival and Formation

For solar-analogue stars, radial-velocity studies show that at least 3% have planetary companions. Lower mass stars are starting to be targeted as well, and a planet has already been identified around a nearby M star (Delfosse *et al.* 1998). In the longer run, constraints for a wider range of stellar types will come from transit studies, while planetary systems around the characteristic lensing population, low mass stars in the Galactic disk and bulge, will be probed by microlensing studies (Gaudi & Sackett 2000).

It is far from clear how the planets that have been found could have formed, given that their orbits are so different from those expected based on formation scenarios of the Solar system. The first identified extra-solar planets, which orbit the millisecond pulsar PSR B1257+20 (Wolszczan & Frail 1992), makes our lack of knowledge even more apparent: there only is a general 'feeling' that is has something to do with a merger of the pulsar with a companion (see Phillips, Thorsett & Kulkarni 1993).

Here, we propose to search for planets around white dwarfs. The first goal is to explore whether planets can survive the last, giant stages of their parent star. Planet survival is not only interesting because of basic astrophysical processes, but also has an (addmittedly somewhat morbid) fascination from an anthropocentric viewpoint. A general expectation would be that planets which have survived being engulfed (Livio & Soker 1984; Siess & Livio 1999) during the star's later evolutionary stages, have orbital separations exceeding 0.5–2 AU. The exact lower limit will depend on the competition between orbital expansion as the central star loses mass (Sackmann, Boothroyd & Kraemer 1993) and orbital shrinkage due to tidal dissipation (Rasio *et al.* 1996).

The second goal is considerably more speculative, viz., to find out whether planets can form following the birth of the white dwarf. The existence of the pulsar planets shows that the possibility should not be rejected outright. Conceivably, planets could form during the last stages of a star's life, when its convective envelope becomes too thin to be supported and shrinks back, perhaps not very uniformly. Better chances, however, seem to be offered by white dwarfs formed in a merger, as the merger might lead to the formation of a dense disk conducive to planet formation.

Both ultra-massive and low-mass white dwarfs may have been produced in mergers. The former, with masses of $\gtrsim 1.2\,M_\odot$, appear very difficult to understand as the products of single stars. They have been suggested to be the products of binary white dwarf mergers, circumstantial evidence being that their mass is about twice the mass of ordinary white dwarfs (Bergeron *et al.* 1991; Livio, Pringle & Saffer 1992; Vennes 1999). For low-mass white dwarfs, with masses smaller than $0.45\,M_\odot$, formation from a single star is impossible, since a putative low-mass progenitor would not evolve off the main sequence in a Hubble time. Likely, these low-mass white dwarfs are the cores of stars whose evolution along the red giant branch was cut short by a spiral in of a companion. Again, a disk may have formed during the spiral-in, and these white dwarfs might thus have planets (Maxted & Marsh 1998). Both the ultra-massive and low-mass white dwarfs appear to be rotating more slowly than predicted by theoretical merger calculations (Segretain, Chabrier & Mochkovitch 1997). A possible explanation of this would be removal of angular momentum by a protoplanetary disk, as is seen in T Tauri stars. (Direct evidence for this is discussed in §3.)

Obviously, planet formation in any of these exotic circumstances would give invaluable pointers to what is and is not important for

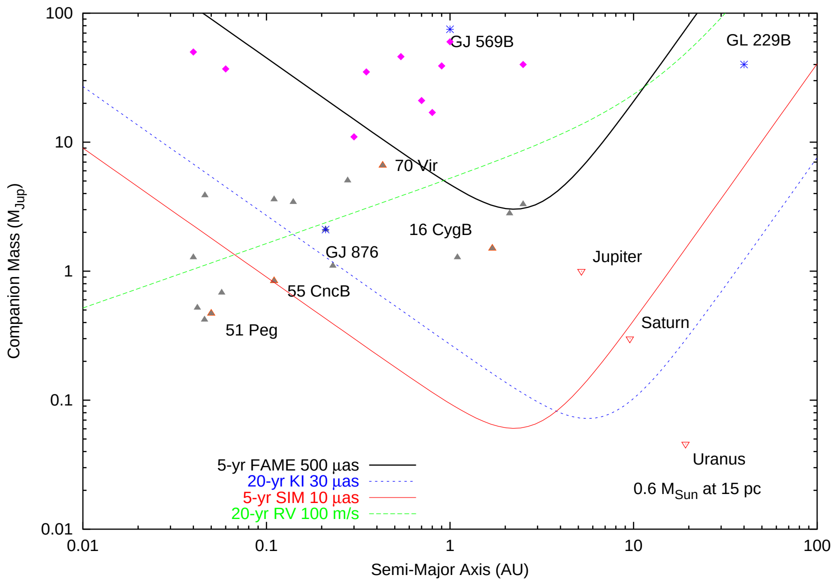

Fig. 1.— *Sensitivity limits for planet detection around white dwarfs. The white dwarf is 0.6* $M_\odot$ *and located at a distance of 15 pc.*

forming them in general.

For some white dwarfs, there is observational evidence for the presence of circumstellar material. In particular, these are cool white dwarfs of spectral type DZ, which show metal lines in their spectrum. Such metal lines are in general not expected in cooler white dwarfs, since sedimentation is rapid (e.g., Alcock & Illarionov 1980). Indeed, most white dwarfs have pure hydrogen (type DA) or helium (type DB) atmospheres. Other, cooler ones show no features at all (type DC) or the Swan bands of molecular carbon (C_2; type DQ; these are due to dredge-up of carbon in a helium atmosphere by a deep convection zone). A likely explanation might seem the accretion of interstellar dust. However, at least for some cases the interstellar medium appears insufficiently dense (Aannestad *et al.* 1993; Zuckerman & Reid 1998). Another possibility is that the accreted material originates in a comet or asteroid cloud associated with the white dwarf (Alcock, Fristrom & Siegelman 1986), although this also has problems (Zuckerman & Reid 1998). In any case, if the accretion is from circumstellar rather than interstellar matter, as seems likely, planets might well be present as well and therefore these white dwarfs would be our prime targets for planet searches.

A target of particular interest is the DAZ white dwarf G 29-38, which not only has metal lines, but also a clear infrared excess (Becklin & Zuckerman 1988). Observations of pulsations by the Whole Earth Telescope observations provide strong constraint on a potential IR companion (Kleinman *et al.* 1994), and the general opinion is that the IR emission is from circumstellar dust. Just as in many main sequence stars (e.g., β Pictoris), this may be a harbinger of a planetary system.

White dwarfs are not suited for radial-velocity studies because their spectra show only few, mostly broad lines. Therefore, astrometry is the only way to probe for planets around white dwarfs (apart from direct detection). Fortunately, astrometry is especially powerful for the wide orbits expected for planets which have survived. Here, we propose high sensitivity observations of a few selected white dwarfs and a moderate sensitivity search of a small, unbiased sample of bright white dwarfs. SIM is the ideal mission for this project; these blue, relatively faint targets are out of reach of FAME and the Keck interferometer.

`Proposed Program.` Our prime targets for detailed, narrow-angle study are the nearest DZ white dwarf (Gliese 35/van Maanen 2; $V = 12.4$, $d = 4.3\,\mathrm{pc}$), G 29-38 ($V = 13.1$; $d = 14\,\mathrm{pc}$), the prototype ultra-massive white dwarf (GD 50; $V = 14.0$, $d = 37\,\mathrm{pc}$), and one well-suited low-mass white dwarf (WD 1614+136 or WD 1353+409; $V = 15.2$ and 15.4, both at 130 pc). With SIM, sub-Jupiter mass objects could be detected (Fig. 1). For our moderate-sentitivity, wide-angle survey, we propose to use an unbiased sample of two dozen bright and nearby white dwarfs drawn from the catalog of McCook & Sion (1999). Most of these will be DA white dwarfs.

Space limitations do not allow us to describing our proposed narrow angle astrometry in detail. The main source of error for white dwarfs will be photon noise; we expect $\sigma \simeq 5.1\,\mu\mathrm{as}$ for $R = 12.5\,\mathrm{mag}$ to $16\,\mu\mathrm{as}$ for $R = 15\,\mathrm{mag}$; here, we assume a sequence of 30-s setup, 30-s on target, 30-s setup and 30-s on reference. The resulting parameter space explored by SIM is shown in Figure 1.

We would like to allocate a total of 100 hrs for the white dwarf project. The highest target throughput is obtained if we can combine our small project with a larger project, because the reference stars can be used for both. One possibility would be to combine with the Shao et al. planet program (of which SRK is the Deputy PI); if both that proposal and this one win, we should be able to make narrow angle observations of four targets. For our wide-angle program, we can select all the white dwarfs that lie within the tiles defined by the main targets of Shao et al. (the nearby stars). There are 58 white dwarfs within 15 pc of the Sun and we expect one third of these to be accessible to the Shao project. Each target will be observed 50 times with 1-min visits (30 s setup, 30 s integration). We would share the burden of wide angle calibrator observations with Shao et al., so that both programmes benefit. The estimated observing times are 75 hours for the the precise narrow-angle measurements and 25 hrs for the broad-brush survey.

3. Iron-deficient post-AGB supergiant (HR 4049) stars

There is a fascinating class of A–F stars, whose metal abundances are severely subsolar (as low as [Fe/H]=-4.8), except for C, N, O, S, and Zn, whose abundances are approximately solar. This abundance pattern is similar to that of the *gas* phase of cool interstellar gas: the metals other than C, N, O, S, and Zn being tied up in dust grains. Yet photospheres of A-F stars are so hot that dust grains could not survive. The subset of these stars which are Population I main sequence stars are known as λ Bootis stars. Venn & Lambert (1990) suggested that these were produced by accretion of dusty circumstellar gas in circumstances when the dust drifted outwards (e.g., due to radiation pressure) relative to the gas faster than the accretion velocity. Then, only the (depleted) gas phase would accrete and would remain on the stable, nonconvective photospheres of A-F stars. This appears possible at low accretion rates (Andrievsky & Paunzen 2000; Turcotte & Charbonneau 1993).

An even more remarkable subclass of these stars are the extremely iron-deficient post-AGB supergiant stars (also of spectral types A–F, both Population I and II). On these we propose to concentrate. These stars show the same pattern of element depletion as the λ Bootis stars, but to even more extreme levels (Mathis & Lamers 1992; Waters, Trams & Waelkens 1992; Van Winckel, Mathis & Waelkens 1992). The similariry in patters suggests a similar origin, but there is a problem: many of the stars have substantial stellar winds, of up to $10^{-6}\,M_\odot\,\mathrm{yr}^{-1}$ (Bakker *et al.* 1996). Assuming $\sim 10^4\,\mathrm{yr}$ passed since they left the AGB, the implied depleted masses are $\sim 10^{-2}\,M_\odot$. It is hard to see how this much matter could have accreted at an earlier post-AGB phase. Furthermore, it appears that *all* of these stars are in eccentric binaries (Van Winckel, Waelkens & Waters 1995), with companions of which no more is known than probable masses, of ~ 0.5–$1\,M_\odot$. The orbital sizes are much less than the size of an AGB star, so the binaries must have survived a common-envelope phase without spiral in. The orbits would certainly have been circularized even before the common envelope phase (Verbunt & Phinney 1995), so the current large eccentricity is most likely due to gravitational interaction with a massive circumbinary disk (Artymowicz *et al.* 1991). Planets may also be forming in the circumbinary disks of these post-AGB stars (Waters *et al.* 1998).

Many important questions remain unresolved: Are the companions main sequence or white dwarfs? What makes binarity essential to the phenomenon? What is the geometry of the circumbinary disk? How much of the circumbinary disk remains, and are the stars still accreting? Is (or did) the dust-depleted gas falling back from within the Roche lobe or from the circumbinary disk?

As an example, consider the prototype of this class, HR 4049. This star has $R \simeq 0.2\,\mathrm{AU}$, $L \simeq 4 \times 10^3\,L_\odot$, and $M_1 \simeq M_2 \simeq 0.55\,M_\odot$. Infrared excess suggests an inner edge for the circumbinary disk of $\sim$5–10 AU, extending to at least 400 AU (Waters *et al.* 1989). The ultraviolet extinction and polarization are modulated with the orbital period (Johnson *et al.* 1999), suggesting that there is also some dust within the Roche lobe, mostly on the anti-companion side. The presence of CO and CS absorption, and the velocity width of the [OI] emission (all presumed to be from the circumstellar disk) suggest that the system is close to edge-on (Bakker *et al.* 1996). SIM can test this suggestion, determine the nature of the companion, and directly image the dust.

`Proposed program.` We propose to use about 20 hours to study HR 4049 and four other members of this class: e.g., BD +39 4926 (V = 9.29), HD 44179 (“Red Rectangle”; V = 9.02), HD 52961 (V = 7.38), and HD 46703 (V = 9.09). Below, we describe what we would learn for HR 4049 in more detail. Similar results are expected for the other systems: all have orbital periods of order a year, and for all the parallax and orbital reflex can be detected with ease.

HR 4049 has $V = 5.5\,\mathrm{mag}$ and is a single-line spectroscopic binary, $P_b = 429\,\mathrm{d}$. At the Hipparcos distance $d \simeq 700\,\mathrm{pc}$, $a \sin i/d = 0.9\,\mathrm{mas}$. Thus, the orbit will be easily measured along with the parallax, and the inclination determined. These measurements will constrain and test models of the dust and molecular line absorption and the emission lines, and will allow to determine the mass of the companion star. The parallax is needed for determining the circumbinary envelope's mass. (Note that currently, HR 4049 is the only one member of this class for which there is a parallax, but the 1 sigma uncertainty is 30%. FAME will improve the measurement for HR 4049, but will not help for the other members of the class.)

Nulling mode[1] would allow easy detection of a companion at 0.9 mas separation from HR 4049, if it is a main sequence star (V = 16); if the companion is not detected, it must be white dwarf. Thus for the first time the question of the nature of the companions of these iron-deficient post-AGB supergiant stars could be answered, confirming or refuting a link to Barium stars. A possibly confus-

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[1] We realize that at the present time we are not allowed to propose the use of nulling mode. As stated in §A, we believe that demonstration of nulling is important for SIM. The observations proposed here is the first of many interesting applications that we intend to develop in the forthcoming years and we hope that this will lead to the restoration of the nulling mode.

ing signal might be present on the other side of HR 4049: the dust proposed to exist within the Roche lobe (putatively responsible for the orbital modulation of the polarization, 0.05% in the red, suggesting $V \simeq 13$). A demonstration that dust exists here would establish that dust can indeed form at a few stellar radii in the wind from a B9 star. The second null at 10 mas is perfectly placed to detect light reflected from the inner edge of the circumbinary disk (expected total between 13 and 15 in V, depending on dust properties).

4. OB Stars far above the Plane

In sky surveys for blue objects at high galactic latitude, such as the Palomar-Green survey, a number of stars have been found which have spectra like those of O and B-type main sequence stars. If indeed young, massive and luminous stars, they are at inferred heights above the Galactic plane of several to tens of kpc, and the question arises how they possibly could have gotten there. Could they have been born at such high distances above the Galactic plane, where presumably so little material is present from they could form?

For some of these stars, high resolution observations have shown that the answer was much more mundane: they were in fact not main sequence stars, but (extreme) horizontal branch, post-AGB and other low-mass, evolved stars with similar effective temperatures and surface gravity. For others, however, similar observations have shown pop I abundances and/or high projected rotation velocities, neither of which are expected for evolved low-mass stars. Still, might they not have formed in the disk, but been kicked out? Disruptions of binaries due to supernova explosions and dynamical interactions in young, dense clusters can lead to "run-away stars," with spatial velocities of hundreds of $\mathrm{km\,s^{-1}}$.

Some of the high latitude O and B stars indeed have high positive line-of-sight velocities, suggesting that they are run-away stars rather than stars formed in the halo. Still, for a few others the inferred evolutionary ages are too small for these stars to have reached their height above the Galactic plane for any reasonable velocity (Conlon *et al.* 1992).

`Proposed program.` We propose to verify that these stars indeed must have formed in the halo, by measuring parallax and proper motion: the former can confirm the large inferred distances, and the latter the absence of extreme velocities. Even one massive star for which it could be shown that it *has to* have formed in situ is sufficient to show that there is clearly more to the halo than we think. We propose to use 20 hours to study about five candidates, two of which are described below. We also note that some of the current candidates may disappear while new candidates may be found, since the study of the early-type stars in the halo is still actively pursued (e.g., Saffer *et al.* 1997; Magee *et al.* 1998; Rolleston *et al.* 1999).

`PHL 346` (Dufton *et al.* 1998 and references therein), a β Cepheid, and therefore massive, at $d \simeq 7\,\mathrm{kpc}$ and $z \simeq 6\,\mathrm{kpc}$, for which the time of flight required appears to be well in excess of the evolutionary age of about 10–20 Myr.

`HS 1914+7139` (Heber, Moehler & Groote 1995), a B2.5 IV with $v \sin i = 260\,\mathrm{km\,s^{-1}}$ with inferred mass between 6 and $10\,M_\odot$, age between 20 and 60 Myr, distance $d \simeq 17\,\mathrm{kpc}$ and height above the Galactic plane $z \simeq 7\,\mathrm{kpc}$, and a small, *negative* line-of-sight velocity. An unrealistic ejection velocity of $800\,\mathrm{km\,s^{-1}}$ is required to reach this large height and turn around.

5. Masses and Radii of Neutron Stars

Neutron stars follow a mass-radius relation that depends on the equation of state (EOS) of the superdense matter in their interiors. For densities up to the nuclear saturation density ($\sim 10^{14.5}\,\mathrm{g\,cm^{-3}}$), the EOS is reasonably

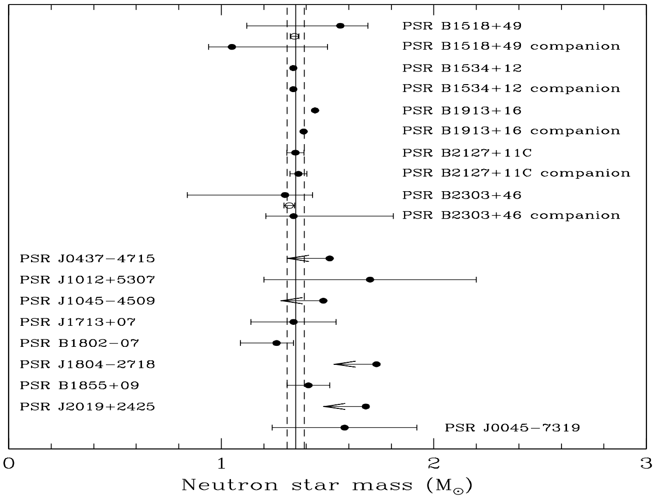

Fig. 2.— *Neutron star masses from radio pulsar systems. Five double NS systems are at the top of figure. Eight NS-WD binaries are in the middle, and one NS - main seq. star binary is at the bottom. Vertical lines indicate* $1.35 \pm 0.04\,M_\odot$. *From Thorsett & Chakrabarty 1999.*

well constrained by laboratory measurements, but for higher densities it is still under much debate. At these densities, our best hope for constraints comes from measurements of neutron-star masses and radii.

For a given EOS, there is a maximum possible mass of a neutron star. For a "soft" EOS (i.e., "compressible" matter), the maximum is near $1.5\,M_\odot$, while for a "stiff" EOS (i.e., incompressible matter) it can be as high as $2.5\,M_\odot$. The best determined dynamical masses, all for radio pulsar binaries, are confined to a narrow range near $1.4\,M_\odot$ (see Fig. 2). However, there is tantalizing evidence from other binaries for masses around a heavy $\sim 2\,M_\odot$ (van Kerkwijk 2000). If confirmed, this would exclude most soft EOS, including almost all EOS in which there is a phase transition in the core (e.g., the Kaon condensate of Brown & Bethe 1994).

SIM will permit significant progress in two ways, one solid and certain to work, another speculative but with higher pay-off for success. The solid method is to expand the current sample of accurate NS masses. At worst, this would lead to a confirmation of the very narrow range inferred currently. This would be very interesting, but we would hope instead to find *unambiguous* evidence of a low or high mass, $< 1.3\,M_\odot$ or $> 2\,M_\odot$. The former would have direct consequences for our ideas of stellar evolution and supernova explosions, while the latter would severely constrain the EOS (e.g., excluding the abovementioned Kaon-condensation models).

Our second way of constraining the EOS is to obtain an accurate measurement of a neutron star radius, by combining flux and temperature as derived from X-ray measurements with a SIM parallax. This would be the first such measurement. If it is also be possible to determine the gravitational redshift from the X-ray spectrum, we get M/R and thus also know the mass; this would give a point on the mass-radius relation, i.e., a direct constraint on the EOS.

`Proposed program: masses.` We will draw our targets from the roughly two dozen X-ray and radio pulsars with bright ($V \lesssim 12$), mostly OBe companions. We will select those that are relatively nearby ($\lesssim 2$ kpc) and have wide orbits (100–1000 day periods), so that the astrometric signal is large (100–600 μas). Furthermore, the wide orbits guarantee minimal interaction, which has plagued the radial-velocity studies of binaries with closer-in companions (see, e.g., van Kerkwijk 2000 on Vela X-1).

From the SIM measurements, we will obtain the astrometric orbit of the OBe companion and the parallax, the former to $<3\%$, the latter always substantially better. From the orbit and parallax, we will derive the inclination and the semi-major axis of the companion orbit in physical units, which, combined with timing orbit of the pulsar, allows us to solve for the masses. We aim for better than 10% accuracy in the final masses.

The above is straightforward when an accurate timing orbit is available. Currently, this is the case for a subset of systems consisting of the one radio pulsar binary and seven X-ray pulsar binaries. These are our prime targets. For some others systems, only the projected peri-astron distance $(1-e)a_{\rm X}\sin i$ is well constrained. We will do simulations to determine for which SIM observations can still lead to strong constraints (in combination with further timing studies, if required). We expect to end up with about ten good systems, for which we can reach $<10\%$ accuracy in the mass using about 3–20 hours of SIM time, depending on the brightness of the companion. The total required time should be around 60 hours.

There are two additional benefits. First, the visual orbit and proper motion provide powerful constraints on natal kicks and and pre-supernova orbits (see §7, Cyg X-1). Second, we will be able to study the influence of the neutron star on the OBe excretion disks, by monitoring the broad ($\sim 500\,{\rm km\,s^{-1}}$) H$\alpha$ and Hβ emission lines as a function of the orbital position (phase differential of the disk lines vs. stellar continuum with orbital position in the frame of the star).

To get an idea of the parameters, we describe the one radio pulsar, and the easiest and most difficult X-ray pulsar binaries.

`PSR B1259-63 -` is the one radio pulsar with a Be companion. It is located at a distance of about 2.3 kpc, and is in a wide (1133 day) and highly eccentric ($e = 0.97$) orbit with the $V \simeq 10$ Be star SS 2883 (Johnston *et al.* 1992). At periastron, the pulsar emission is eclipsed by a powerful equatorial wind from the companion (Melatos, Johnston & Melrose 1995). From timing derived parameters we estimate $\pi \approx 0.5$ mas, and a peak-to-peak orbital signature of $\sim 250\,\mu$as.

`X Persei -` the nearest Be/X-ray binary, composed of a O9.5 III-Ve star and a neutron star in a wide orbit with $P_{\rm orb} = 250$ d and $e = 0.11$. The Be star is bright ($V \simeq 6$), and the distance to the source is 350 pc. The expected peak-to-peak orbital signature is about 600 μas.

`A 0535+26 -` an X-ray pulsar with a $V = 9$ O9.7 IIIe companion, at ~ 2 kpc. The orbital period is relatively short, at 111 d, resulting in an astrometric signature of only $\sim 100\,\mu$as.

`Proposed program: radius.` We hope to use Aquila X-1 to determine the first accurate neutron star radius. Aql X-1 is a transient that shows regular outbursts, and is known to contain a neutron star, since type I X-ray bursts are seen, which are due to a thermonuclear explosions on a neutron star surface. When the source returns to quienscence, a small amount of residual X-ray emission is observed. It has been hypothesized that this reflects residual thermal emission from the neutron star surface (for mechanisms which might maintain the core at 10^8 K and the surface at 10^6 K, see Brown, Bildsten & Rutledge 1998). If so, one can derive accurate temperatures and fluxes using the X-ray spectrographs on board Chandra and XMM-Newton. Possibly, one will be able to identify features in these spectra; if so, one can determine the gravitational redshift (expected $z_{\rm GR} = GM/Rc^2 \simeq 0.2$).

By the time SIM is launched, it will be clear whether the above works. If so, we propose to use SIM to obtain an accurate (5%) distance for Aql X-1, by observing it during its outbursts, when it is bright ($V \simeq 15$; estimated distance 2 kpc). Combining the parallax with the temperature and flux inferred from the X-ray measurements, will allow a direct determination of the radius. This will already be fantastic. If also the gravitational redshift was measured from the X-ray spectra, the result will be truly unprecedented: a point in the mass-radius diagram for neutron stars!

6. The Origin of LMXBs

In low mass X-ray binaries (LMXBs) the presence of a low mass star so close to a NS is surprising. At current orbital separations, the secondary is within the main sequence radius of any massive progenitor, and far within the radius of a pre-supernova star. In addition, in the formation of a $1.4 M_\odot$ NS from a $> 10 M_\odot$ progenitor, more that half the mass of the binary is lost, and so the system should have become unbound if the mass ejection was symmetrical.

Two mechanisms have been proposed to solve the above problem. The first 'standard' scenario involves an initially wide binary. Evolution of the primary (NS progenitor) leads to a common envelope stage and inspiral of the low-mass secondary (Verbunt 1993). The core of the primary, a helium star, continues to evolve and explodes as a supernova. However, in order to explain the properties of the observed orbits and space motions of LMXBs a properly oriented kick is needed at the time of the supernova (van den Heuvel & van Paradijs 1997, Brandt & Podsiadlowski 1995). The second scenario involves accretion-induced collapse (AIC) of a massive white dwarf. In this case only the binding energy equivalent ($0.2\ M_\odot$) of mass is lost and the system remains intact in a symmetric collapse. However good massive white dwarf candidates for AIC have never been found, and the Galactic distribution of LMXBs is not consistent with the low birth velocities of symmetric AIC, so natal kicks appear to be required here too (van Paradijs & White 1995). Tests of these models depend depend largely on the sky distribution and the kinematics of LMXBs (Johnston 1992, van Paradijs & White 1995). The kinematics are quite poorly known, so the addition by SIM of proper motions and parallax will be valuable. When all three components of the space motion of a single-line spectroscopic binary LMXB are known, one can test consistency of the inferred initial orbit with the kick velocity (for an example of the surprising conclusions that may result, see the work on Cir X-1 by Tauris *et al.* 1999, and on black hole binaries by Nelemans, Tauris & van den Heuvel 1999).

We propose observations of the brightest LMXBs ($V \lesssim 16$) to obtain distances and systemic speeds. We expect median parallaxes around 0.2 mas, and proper motions of $\gtrsim$ mas yr^{-1}.

7. The Most Massive Stellar-Mass Black Hole?

For years, the best indication for the existence of black holes came from the X-ray binary Cygnus X-1. Because of uncertainties on the mass of the companion, however, the evidence never became beyond doubt (which led to the famous wager on Cyg X-1 between Thorne and Hawking).

During the eighties, however, attention switched to a new class of systems called X-ray novae, a subgroup of the low-mass X-ray binaries, prototypes of which are the well known systems A0620−00 (McClintock & Remillard 1986) and V404 Cygni (Casares, Charles & Naylor 1992). These systems show outbursts due to episodes of strongly enhanced accretion. The outbursts are accompanied by rapid optical brightening, $\Delta V \simeq 10\,\mathrm{mag}$, and are followed by a decay of months. After the source has subsided into quiescence, the accretion disk no longer dominates the optical flux, rendering the companion visible. Spectroscopy of the low-mass companion then allows the mass function to be measured, giving a lower limit to the mass of the compact object. These limits have provided, by far, the strongest case for the existence of black holes in nature.

To get a mass estimate rather than just a lower limit, line broadening and ellipsoidal variations in the photometric lightcurves are observed, from which the inclination and mass ratio are inferred using models. The assumptions underlying these models are that the companion fills its Roche lobe, that it rotates synchronously with the orbit, and that its surface brightness can be described adequately by black-body emission (pathetically few studies have used proper stellar atmospheres). For some systems, very massive, $\gtrsim 10\,M_\odot$, black holes have been inferred, which has direct implications for the terminal evolution of very massive stars ($\gtrsim 25\,M_\odot$; Timmes, Woosley & Weaver 1996), a topic that is ill-understood. Here, we propose to confirm the mass estimate for the system which appears to harbour the most massive black hole.

`Proposed program: V404 Cygni` We propose to measure the orbit of V404 Cygni, the companion to the X-ray nova GS 2023+34, which has the highest mass function of any compact object ($6.1\,M_\odot$; Shahbaz *et al.* 1994).

V404 Cyg is a low-mass (0.2–$1\,M_\odot$) star in a 6.5-d orbit around the putative BH. The projected semi-major axis for the optical star, $a_1 \sin i$, is approximately $28\,R_\odot$. Combined with the inclination as estimated from ellipsoidal modeling of the infrared lightcurve, one infers $a_1 \simeq 37\,R_\odot$ and a BH mass near $12\,M_\odot$ (Shahbaz *et al.* 1994; Casares & Charles 1994).

The expected astrometric signature is 80–$120\,\mu$as, and a 10% determination should be within reach of SIM (30 hr). At the same time, the distance will be determined to much larger precision. With the measured orbital elements, we will be able to verify the black-hole mass determination, as the mass ratio is small due to the puny companion. By measuring the inclination, we can also ascertain the validity of the assumptions underlying the modeling of the ellipsoidal modulations.

`Cyg X-1` We propose to observe the classic source Cyg X-1. We will determine the orbital sky-orientation, inclination and proper motion. Powerful constraints could be placed with these, e.g., if the BH does not receive a natal kick, the space velocity will lie in the orbital plane, with the velocity perpendicular to the line of apsides. This permits us to deduce kick velocities and pre-supernova orbits for BH systems (see `GRO J1655−40` in §A.5) with far greater certainty than possible before. Unfortunately, in Cyg X-1 mass determination is limited by uncertainties in the mass of its supergiant companion (Herrero *et al.* 1995), however, we will examine this issue in greater detail.

8. SS 433

SS 433 is a remarkable system. It went from complete obscurity in 1978 (2 publications) to more than 120 publications in 1981 and its own review in ARA&A (Margon 1984). The system is at a distance of 4–5 kpc and heavily absorbed ($A_V \simeq 8$), but still has $V \simeq 14$, which makes it one of the most luminous ($M_V \simeq -7$) objects in the Galaxy. This bizzare star was found to have strong, broad Balmer and He-I emission lines in the optical, as well as a number of other broad emission features at unfamiliar wavelengths, which change on a matter of days. The latter turned out to be Doppler shifted features, showing two sets of shifts, sometimes overlapping at a mean redshift of $12 \times 10^3\,\mathrm{km\,s^{-1}}$ and sometimes being apart up to $50 \times 10^3\,\mathrm{km\,s^{-1}}$ in redshift and $30 \times 10^3\,\mathrm{km\,s^{-1}}$ in blueshift.

It is now clear that these large motions are the result of two collimated, oppositely aligned jets, with a stable ejection speed of about 0.26c. The Doppler shifts vary because the jets precess, with a period of 164 d. The precessing jets are clearly visible as large helical structures in radio images. Despite considerable study, however, it is still not clear what kind of compact object is present in SS 433, with estimates varying from a massive black hole (5–10 $M_\odot$) down to a regular neutron star (D'Odorico *et al.* 1991).

`Proposed program.` We propose two separate sets of observations of SS 433. The first is a series of short observations (possibly narrow-angle) of the SS 433 continuum over various orbital phases, in an attempt to determine the visual orbit of the system. If no clear astrometric signature is observed, which is possible if the system photocenter is too close to its barycenter (it is not clear what are the fractional contributions to the optical flux from the star and the accretion disk around the compact object), we may abandon the effort. The expected orbital signatures are a just detectable 10 μas for a neutron star compact object and an easily manageble 60 μas for a 10 $M_\odot$ black hole.

The second set of observations we propose are two long ones targeting the motion of line-emitting clumps of ejecta. The detector pixels spans about 1800 $\mathrm{km\,s^{-1}}$, easily resolving the large velocity shifts of $\sim 10^5\,\mathrm{km\,s^{-1}}$ perpendicular to the line of sight, as well as the width of individual broad ($\sim 5\times10^3\,\mathrm{km\,s^{-1}}$) lines. The H$\alpha$ equivalent width is $\sim$600Å, implying that exposures of about 10^3 s should yield 10 μas accuracy when averaged across the Hα profile. We hope to get time-elapsed data on the ejection and kinematics of the line emitting ejecta, from the unprecedented small scales of 0.01 AU to when matter leaves SIM's diffractive field-of-view (which subtends about 10 AU at the distance of SS 433).

Table 1
Rough Project Breakdown

Subtopic	Hours
White Dwarf Planets	100
λ-Bootis Stars	20
OB Stars above plane	20
Neutron Star Binaries	60
Low Mass X-ray Binaries	30
Black Hole Binary	30
`SS 433`	30
Frame Tie `PSR J0437−45` only	10
Total	300

9. Note on the Observing Times

In the above sections, we have described a number of projects. In total, these require about 300 hours of observing time; a rough project breakdown is in Table 1. Here, some closing notes on how these times were derived.

The white dwarf planets sub-program uses a combination of wide and narrow angle observations, and the time estimates were given in somewhat more detail there. For all other sub-programs, the time estimates are currently based on the wide angle astrometry (WAA) calculator. For determinations of orbits, we increased the time requirements as appropriate for the estimation of additional parameters over and above the usual five. We will investigate the narrow-angle (NAA) mode for those sources with small (estimated) astrometric signal ($\lesssim 100\,\mu$as). The clear advantage of NAA is the increased sensitivity (chopping reduces thermal drift, a nearby calibrator decreases field errors, etc.); there will be little savings in time in switching from WAA to NAA. In order to use NAA, we would need to ensure that a grid star quality reference star ($V = 12$, quiet at the 4 μas level) is available within 1 degree of the target. We will work with other groups (e.g. the Grid group, and the Shao et al. planet search group) in identifying our reference needs.

A. Contributions to the Mission

In this section we summarize the expected contributions of the PI and his team to the Space Interferometer Mission. Unlike the other mission scientist positions, the role of the Inter Disciplinary Scientist (IDS) is not well defined in the Announcement of Opportunity. We interpret this to mean that the IDS team has broad flexibility in its anticipated contributions to SIM, the main goal being to maximize scientific return from the mission, specifically in those areas of scientific enquiry unlikely to be covered by Key Project teams.

To start with we note that the PI has a track record of working in diverse fields (radio, optical and X-ray astronomy; radio and optical interferometry; neutron stars, pulsars, gamma-ray bursts, brown dwarfs, interstellar medium). The PI team is equally diverse and includes theorists (Phinney and Hansen) who have attacked a broad range of topics in astrophysics and observers who have worked in diverse fields (van Kerkwijk and Vasisht). See appendix B for the CV and research interests of the team members.

In addition, we note that Vasisht is a staff member of the Keck Interferometer project with the responsibility for the critical fringe detection and tracking system. The PI's involvement in interferometry starts from his PhD project of the design and commissioning of a radio-linked interferometer at Arecibo, the development and leadership of speckle interferometry and the technique of non-redundant masking at Palomar, his involvement in the precursor to SIM (the Orbiting Stellar Interferometer, OSI), his participation in the SIMSWG, and most recently his role in the development and usage of the Palomar Testbed Interferometer (PTI) and the Keck Interferometer project.

Below we give three specific examples of issues – frame tie, calibration issues specific to binary stars and the sensitivity of SIM to long-period companions – that we hope to study, should our proposal succeed. This is followed by a brief discussion of the astrophysical use we believe we can make of the vast grid star database[2].

The status of the nulling mode is at present unclear. It is our firm opinion that nulling is an important element of SIM and critical to the overall goals of Origins program. We believe that possible scientific returns from the nulling mode have not been properly developed by either the SIMSWG or the project. This is understandable since nulling is a specialized mode. Just like polarimetry (a niche technique), however, nulling has the ability to return critical results. Should we be selected, we intend to develop a strong *science* justification for nulling. We will coordinate our effort with all interested, the nulling/imaging scientist and also R. Allen of STScI.

A.1. Frame Tie

Three thousand "grid" stars define the astrometric frame of SIM. This frame is not inertial, however, and furthermore the SIM grid is not easily related to other (existing) coordinate frames. To this end, it is anticipated that SIM will observe between 50 and 100 radio quasars with the dual goals of anchoring the SIM frame with respect to the most inertial frame we know of (the distant Universe) as well as to relate the SIM frame to the currently most precise and accurate astrometric frame, namely, that defined by compact radio sources. This frame is also called as the International Celestial Reference System (ICRS; Ma *et al.* 1998) and is defined by radio VLBI observations of about 600 sources.

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[2] The Grid Star Project will observe three thousand stars repeatedly and use one quarter of the total mission time. To our knowledge there has been no discussion of how the project will deal with proposed astrophysical exploitation of the grid database.

Millisecond pulsars are the only other sources in the sky located to a precision which challenges the ICRS. However, the singular advantage of millisecond pulsars is that their position[3] is determined with respect to the ecliptic frame. In contrast, the ICRS is determined with respect to the Earth's equatorial frame.

Spacecraft navigation is done with respect to the ecliptic frame and for this reason there has been premium attached to defining astronomical sources in the ecliptic frame (see Bartel *et al.* 1996). The ecliptic-SIM tie can be accomplished by observations of solar system objects (e.g., asteroids) or through pulsars. However, the latter will not be observable with SIM due to their low surface brightness. Below we show how observations of binary millisecond pulsars, specifically those with a visible white dwarf companion, can tie the SIM frame to the ecliptic frame at the 10–20 microarcsecond level.

Gaume et al. (1999) review the SIM frame problem and investigate a subset (28 in all) of ICRS quasars, namely those which are bright (18th magnitude or brighter) which can be used to tie SIM to the ICRS. These quasars can be *formally* measured by SIM to a precision of 7 μas. This subset can be expected to be significantly expanded once the FIRST radio survey (White *et al.* 2000) has been completed. This survey will identify even brighter (17th magnitude) radio loud quasars.

It is too early to comment on the *accuracy* (as opposed to precision) of the ICRS-SIM tie. Likely, the accuracy will be limited not by the precision with which SIM can measure the ICRS quasars, but by changes in the emission of these compact radio sources (jets, ejection of blobs), which can cause variations of the order of a milliarcsecond over the duration of the mission are common (see Gaume *et al.* 1999). Clearly, the *accuracy* and the *precision* of the SIM-ICRS frame tie will not be any better than the accuracy of ICRS itself. At the present time, the formal accuracy of the ICRS is 170 μas and, as noted by Gaume et al. (1999), there are excellent prospects of improving this accuracy by careful monitoring and modeling the source variability and by rejection of particularly variable sources.

Independent of the ICRS-SIM frame tie issue, we propose to carry out observations of two binary millisecond pulsars, one in the north (PSR J1012+5307; Nicastro et al. (1995)) and the other in the South (PSR J0437−4715, Johnston et al. 1993). Both are nearby and their white dwarf companions are relatively bright, having R magnitudes of ~ 19 (Nicastro *et al.* 1995) and ~ 20 (Bell, Bailes & Bessell 1993), respectively.

`PSR J0437−4715` is a 5.7-ms pulsar with a white dwarf companion in a 5.7-day orbit. It is the brightest radio millisecond pulsar and, at 180 pc, also one of the nearest. It has been timed extensively at Parkes (in a collaborative effort involving our group at Caltech, R. Manchester of the Australia Telescope National Facility and M. Bailes's group at Swinburne University, Melbourne). Using a correlator system developed by our group, the pulsar has been timed to 0.5 μas precision and the position (as of 1997, or the first two years of data) was determined to a precision of 50 μas (Sandhu *et al.* 1997). This precision is limited by systematics within the backend (polarization purity, digitization noise, etc.).

We have developed new techniques to overcome the polarization impurity problem (Britton 2000) and the systematics due to

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[3] The position is derived by noting the variation of the arrival time as the Earth revolves around the Sun. The position precision is $\sigma_{TOA}/2A \sim 200\sigma_{TOA}\mu$as where σ_{TOA} is the precision of a single time-of-arrival (TOA) measurement and $A = 500$ is the orbital radius of the earth (in light seconds). The final precision is limited by number of measurements (which improves as $n^{1/2}$) and systematics due to pulsar signal propagation and our knowledge of the solar system ephemerides.

digitization (Jenet & Anderson 1998). Furthermore, we have developed new hardware which allows optimal extraction of TOAs (by software processing of baseband recording; Jenet *et al.* 1998). This sustained effort spanning nearly a decade of hardware and supercomputer software developments is now paying off. We are now routinely achieving a TOA precision of 250 ns and have already demonstrated short-term precision of 100 ns. By next year, we anticipate long-term precision of 100 ns. Thus, the position of this pulsar will be known to better than 10 μas by the time SIM is launched. [The proper motion will be known to even better precision given our long temporal baseline.]

`PSR J1012+5307` is a bright (30 mJy at 430 MHz, 3 mJy at 1.4 GHz), nearby (500 pc) 5-ms pulsar in a 14-hr orbit with a white-dwarf companion. This object has not been as intensively timed as other pulsars (but this will change soon, when the 100-m Green Bank Telescope becomes operational). The pulsar has parameters (flux, period, dispersion measure) similar to those of the well studied pulsar, PSR B1855+09 (Kaspi, Taylor & Ryba 1994). This allows us to scale and estimate the expected TOA accuracy on the Green Bank Telescope: 1 μas (40 MHz bandwidth) to 0.5 μas (160 MHz, at 1.4 GHz). The corresponding astrometric precision for the position is about 50 μas. This will gradually improve with time and reach about 25 μas by the end of the mission.

According to the SIM exposure calculator (sim.jpl.nasa.gov), of order 15 hours (per target) would be sufficient to determine the positions (end of mission) to 20 μas (or better). There is an added bonus in obtaining 10 μas precision observations of PSR J0437−4715: we will be able to determine the orbit to 3% precision and thereby obtain the masses of the neutron star and the white dwarf to 10% precision. Recall that four of the binary parameters are known very precisely from pulsar timing and thus the SIM measurements can be profitably combined with the timing observations. It will be especially interesting to obtain a precise mass of this particular pulsar, since it has been "recycled" by accretion of matter from what is now the white dwarf. The total accreted mass should be $\gtrsim 0.5\,M_\odot$, and thus this measurement may well lead to the best lower limit on the maximum mass a neutron star can have. [PSR J1012+5307 will exhibit astrometric signature not detectable by SIM due its smaller orbit and greater distance.]

`Proposed Activity.` Above we have argued the value of observing with SIM the two optically brightest milllisecond pulsar systems. These observations will help tie the SIM frame to the ecliptic frame at the 10–20 μas level. We see it essential that both pulsars be observed and by good fortune the two pulsars are located in different hemispheres. We argue that the proposed observations benefit the entire project and as such the time for these observations should come from the Grid project. We see our role as motivating these observations and undertaking the necessary ground based program (specifically ensuring that the precision timing continues at the highest level of precision). However, should our proposal be successful, we are willing to negotiate some sharing of observing time given the astrophysical returns from observations of PSR J0437−4715 system.

A.2. Binary Stars: Calibration Issues

To date, the SIM project has not accorded high priority to binary stars. The justification is that most targets of interest are effectively single stars. However, in our opinion, SIM will end up observing many interesting binaries for at least two reasons.

First, binaries will form the prime target for tests of stellar structure and evolution theory, especially binaries which are also spectroscopic binaries and have periods smaller than the duration of the mission. Only for such binaries can one determine masses to the level of precision that is now considered interesting in stellar astronomy, better than 1%. To have successful binary observations, however, requires that we address the amplitude calibration issue – so far not a major focus for the SIM project.

Second, as argued later (§A.3), there are some advantages to using binary stars for the grid. The current view of the project is to use metal-poor K giants for the grid. The grid issue is still not settled, however, and it may well be that the grid will include a reasonable number of such binaries as a cross-check against the distant giant reference stars; see §A.3 for further details.

Motivated by the potential astrophysical returns and the needs for the project, we are prepared and eager to work on the calibration issue for binary stars. This is a topic of some interest to S. Shaklan of the SIM project and we acknowledge extensive discussions with him. We now summarize the technical issue relevant to the proposed work.

Binary star observations with SIM fall into four classes: (A) observations of systems that are unresolved by the interferometer baseline (separation $a \ll 10$ milliarcsecond); (B) systems that are unresolved by individual apertures, $0.01 \lessapprox a \lessapprox 0.4$ arcsecond; (C) systems that are partially resolved, $0.4 \lessapprox a \lessapprox 2$ arcsecond), and (D) visual systems, $a \gtrapprox 2$ arcsecond.

In regime (A), the stellar images appear as point spread functions (PSFs) indistinguishable from that of a single star and thus the astrometric center is the same as the photocenter. In this regime, data processing and calibration are the same as for a single star. That is, SIM determines the astrometric position from the measured phase across the spectrum.

In regime (B), the PSF remains indistinguishable from a single star but the interferometer resolves the two components. The phase delay has two distinct components: the primary component, like a single star, yields a term that is linear in wavenumber; the companion adds an oscillating term whose frequency indicates the separation and whose amplitude reveals the relative luminosities.

The direct measure of angular separation is ultimately limited by SIM's bandwidth and spectral resolution. The bandwidth (0.5–0.9 microns) demands a stellar separation exceeding 22 mas to observe a full period of oscillation across the spectrum. (There is a significant noise penalty, just as with orbital determination, when less than one period is measured.) Nyquist sampling using a limited number of spectral channels (80) requires a stellar separation of less than 1 arcsecond. At this separation the stars are resolved by the subapertures and other problems arise (see below).

Note that the angular separation measurement is highly differential and many significant sources of error (e.g., internal and external metrology, beam walk, thermal deformation) do not affect the measurement. On the other hand, the measurement requires calibration of instrumental dispersion, internal reflections, and scattering, all of which cause an oscillatory phase structure in the spectrum.

In regime (C), SIM's 25 cm apertures resolve stars with separations exceeding 0.4 arcsecond, but for separations less than 1 arcsecond both stars still pass through the field stop. Several calibration difficulties arise in the presence of two closely spaced PSFs: these are diffraction and beam walk due to centroiding errors, CCD pixel calibration, and coherence length limitations.

The nominal guiding policy for SIM is to repeatedly position the target star to 30 mas on the CCD. This is to compensate beam walk jitter; when the star light encounters slightly different parts of the optical train, it encounters bumps and valleys on optics that are not sampled by a properly aligned beam. This changes the mean optical path by an amount that is significant compared to the narrow-angle astrometric requirements. For partially resolved binaries, the guiding algorithm can partially compensate for the shift of the photometric center of light but not for both stars simultaneously. Thus, some beam walk is inevitable. The systematic errors appear with the periodicity of the binary system.

Another source of error is diffraction. The spatial filtering properties of the 2-arcsecond field stop are altered when one or both of the sources appear off-axis. This source of error would again manifest itself with the orbital period of the binary system.

Finally, the finite coherence length of the interferometer over a 1-arcsecond field affects the interpretation of the measured signals. The 80 wavelength bins have a resolution of about 140, resulting in a coherence length of roughly $\pm 100\,\mu$m in the R band. Thus at 1 arcsecond, the fringe visibility will be significantly reduced. To further complicate the issue, the visibility reduction is a function of the relative orientation of the binary to the interferometer baseline. Without proper calibration this can lead to both astrometric and photometric errors.

In regime (D), the system is treated as two separate stars. At the μas level, diffraction from the brighter star while observing the fainter one may be an important error source. When the baseline is oriented nominally perpendicular to the binary separation, the forward-scattered light will form high-visibility fringes. The light level may be of order 0.001 of the central peak. For high-precision astrometry, this probably limits the maximum allowed magnitude difference to $\sim$ 5 magnitude.

`Proposed Activities.` For SIM, the key issue is amplitude calibration at the 10^{-3} level. There is no reason why this level of calibration cannot be achieved; we remark that we are now approaching 1% amplitude calibration with ground-based interferometers. But, as noted above, binarity may be an issue. We are prepared (in our capacity as member of the Science Team) to ensure that these problems are solved and that the requirement of adequate amplitude calibration will be met. We note that we have already some experience in dealing with some of these issues, specifically with modelling the fringe visibility of binary stars, from our on-going program at the Palomar Testbed Interferometer (PTI; e.g., Boden *et al.* 1999). If our proposal were to succeed, we anticipate working closely with Shaklan and Boden of the SIM project.

A separate issue is to think of potential astrophysical returns offered by the highly differential nature of regime (B) – a topic which we would like to explore during the forthcoming prepatory phase.

A.3. The Grid and the Problem of Distant Companions

Much of the discussion about the grid has centered on potential astrometric perturbations on timescales short compared to the duration of the mission – primarily planets with orbital periods less than the duration of the mission. SIM has excellent sensitivity to long-period planets, however, just those for which radial velocity (RV) measurements lose sensitivity. Thus, it is critical that SIM's sensitivity to long-period objects not be compromised.

The key issue here is possible distant companions to reference stars, which cause acceleration of the reference star and thereby limit the use of the reference star in identifying long-period companions in target stars. As a part of our contribution to the mission, we intend to look into this important issue and identify potential solutions.

We now summarize the current understanding on the general issue of grid stars.

As of the last SIM astrometric workshop (in Pasadena, January 20, 2000) the consensus was to use metal poor K giants for the SIM grid. Patterson et al. (1999) have commenced an imaging survey with a set of special filters designed to separate giants from dwarfs. They anticipate an areal of density of 0.1 per square degree at the 12th magnitude level. Their abundance, their distance (1–2 kpc) and luminosity make metal-poor K giants desirable as grid stars.

K giants, however, while admirable for reasons listed above, have two problems. First is the contamination by possible planetary companions in the orbital range 2–10 AU and mass in excess of 1 M_J. These will result in astrometric signatures detectable at the level of the grid, 4 μas; see Figure A3. Some members of the community have proposed identifying planetary companions by RV studies. We are concerned, however, whether the required 30 m/s precision can be achieved for all grid stars. The existing literature is sparse and not uniformly encouraging (see Hearnshaw & Scarfe 1999 for recent reviews).

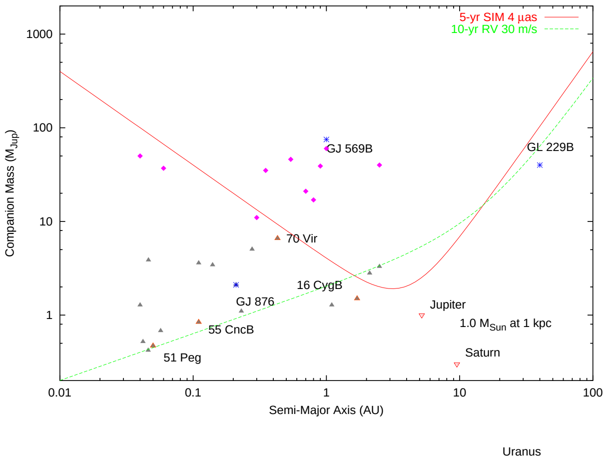

Fig. A3.— *Limiting astrometric perturbation sensitivity for a reference star at 1 kpc. RV studies can identify all contaminating companions with orbital periods comparable to the duration of the RV survey (especially if the reference star is at 2 kpc). However, this requires a long-term precision of 30 m/s – an open issue with K giants.*

The second concern is stellar binarity. To detect stellar companions, especially those with separations in the range 50–250 AU, requires AO with excellent dynamic range. [Note that little is known about the frequency of brown dwarf companions to metal-poor stars.] Should such companions exist, they will induce an acceleration which can only be modeled by referencing the observations with another reference star known not to have any acceleration or an ensemble of stars with random accelerations.

At the Pasadena SIM grid workshop, we suggested the possibility of using wide and/or eccentric G star binaries as candidates for the grid. By the virtue of their binary companion, these stars will neither house planets over a range of orbital periods (Holman & Wiegert 1999), nor have have distant companions (up to a separation of at least ten times the binary separation). Thus, they can act as reference stars for the determination of acceleration in other stars.

`Proposed Activity.` We propose to look into the issue of SIM's response to distant companions, specifically the issue of reference stars contaminated by distant ($\lesssim$50 AU) companions. One particular possibility we will study is the inclusion of a small fraction (10%?) of eccentric G dwarfs with long orbital periods, 5-50 yrs. As argued above, such objects are unlikely (especially if filtered by AO observations) to possess distant-companions and thus can provide a zero-point for determination of acceleration. The cost-benefit analysis of including these stars in the grid needs to be done. (In the absence of such "zero-acceleration" references, one would average tens of grid stars to obtain the reference for acceleration. Thus, the issue is whether a clean object is worth the increase of 10% in the number of reference stars relative to the covariance introduced by using an ensemble of possibly contaminated reference stars).

It may well be there are other solutions and we are not excluding any ideas at the present time. Our main goal is to bring this issue to the attention of the Science Team and then work on possible solutions. [We have been informed that S. Turyshev of the SIM project is equally concerned about this issue and should we be successful we will coordinate our work with that of Dr. Turyshev.]

A.4. Astrophysical Uses of the Grid Database.

As stated earlier, to our knowledge, there is no policy regarding possible exploitation of the vast grid star database for uses other than the grid. One particular application (and perhaps the richest), the determination of the PPN parameter γ, is a natural byproduct of grid closure. Indeed, this issue has been studied in great detail by Dr. Turyshev of the SIM project (Turyshev 1999). Below, we propose three specific uses of the grid database.

`Planets to Grid Stars.` Each of the 3000 grid star will be observed about 25 times during the course of the mission. This is a great data base to determine planetary frequency. We know very little about the propensity for the currently popular grid stars (metal-poor K giants; these are members of the thick disk with a metalicity of 0.1 that of the Sun). There has been some speculation that planet formation is sensitive to the metalicity of the parent star (Gonzalez & Laws 2000). Indeed, the absence of systems similar to 51 Peg in the extensive on-going HST investigation of the cluster 47 Tuc (PI, R. Gilliland; `http://www.aas.org/publications/baas/v32n2/aas196/317.htm`) supports this conjecture (the metalicity of 47 Tuc, [Fe/H] = −0.76, is similar to that of the thick disk).

The details of the grid campaign are yet to be worked out. One scenario is to start with a large list of grid stars (filtered by extensive RV studies) and then drop objects exhibiting clear duplicity signals as the mission proceeds. As discussed above, however, planets and brown dwarfs in wide orbits (say, periods of 5 years or longer) will only get identified towards the end of the mission, and distant stellar companions (less than 300 AU) are unlikely to be identified by AO observations. Both these will lead reference stars to suffer from acceleration.

Our main interest is to develop a clear plan so that both the stars which have been dropped earlier in the mission as well as the final grid stars can be used to quantitatively address the issue of planets and brown dwarf companions to grid stars. We are keen to have an active voice and role in this matter.

`Galactic Dyanmics with Grid Stars.` The astrometric grid stars will provide an excellent dataset to redo the determination of the mass density in the solar neighbourhood. The standard reference in this regard is still the work of Kuijken & Gilmore 1991, based on star counts extending to heights of 1.1 kpc and a sample numbering 500 stars. The astrometric grid will extend to several kpc and will total about 3000 stars. The detailed proper motion and radial velocity information will also allow us to perform a much better reconstruction of the distribution function than ever before. In particular, we will be able to reconstruct the three dimensional velocity ellipsoid, something Kuijken & Gilmore could not do, and which was one of the primary uncertainties in their determination. Here, we will evaluate SIM's performance versus that of FAME.

A.5. Preparatory Science

Besides the mission specific preparation outlined in this appendix, considerable preparatory work is required in order that our proposed program reach its required goals. We have presented a rough time budget (see table 2) based on expected

SIM performance limits, however, we must carry out extensive simulations in order to determine the exact time requirements of our program on a per target basis. As mentioned earlier, we aim to ensure that we can find reference stars of the appropriate quality in order to observe some of our targets in the narrow angle mode. By working closely with others, such as the Grid and planet-search groups, we can identify these.

We need further support observations, e.g., accurate pulsar timing at Parkes and Green Bank for the frame tie program, deep X-ray observations of Aql X-1 to obtain the best possible spectra with currently orbiting and future (Constellation-X) observatories. Furthermore, we need a deeper understanding of the quality of currently existing data on our targets. We may obtain further X-ray timing data, optical RV curves and better spectroscopic estimates of the optical photocenter in various systems to back up our mass-measurement program. We need to understand the level and timescales of variability in our targets, and the systematic errors associated with these. For targets bright in the near infrared ($K \lesssim 11$) for which suitable nearby (< 1 arcmin) references are available ($K \lesssim 17$), we will demonstrate feasibility with astrometry at the Keck Interferometer at the ~ 30 μas hr$^{-1/2}$ level. Over the years, we expect that a series of graduate students and postdoctoral scholars will assist us in the above.

Finally, we will closely inspect other targets that are not yet included in our list. A closer look might warrant the addition of a scientifically valuable source to our target list. A few examples illustrate this point. We may refresh our list of massive X-ray binaries (for NS masses), if better timing orbits for select systems become available over the next several years. We will examine the feasibility of observing, faint ($V > 12$) and photometrically variable binaries with tight orbits such as the exotic microquasar GRO J1655−40 (Nova Sco 94) which is a black hole binary with large systemic velocity (orbital reflex 25μas; $V \simeq 17$), and the classic low mass X-ray binary Sco X-1 (reflex 5μas; $V \simeq 13$). These sources are bound to require full narrow angle accuracy. GRO J1655−40 is an interesting target for reasons of BH mass, high systemic velocity (see §7; Cyg X-1) and relativistic jets in high-state. Sco X-1, the brighest X-ray source, is a prime candidate for detection of gravitational waves with LIGO II (cf. Bildsten 1998, Andersson, Kokkotas & Stergioulas 1999), but the search would be hindered by our current lack of knowledge of the neutron star's radial velocity ephemeris (Brady & Creighton 2000) The SIM measurement of the reflex motion of the accretion disk will provide a valuable approximate ephemeris.

We have already outlined the effort, and level of consultation with SIM intrument specialists required to address calibration issues (§A.2), and issues with the contamination of Grid stars (§A.3). Considerable effort will be spent in ensuring pulsar timing precision to 10-20μas residuals in both hemispheres, for our frame tie proposal (§A.1).

We believe that SIM as a mission has unique scientific potential, and it may well be the only mission of its kind for a long time to come.

B. Resumes

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Positions

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Honors

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Waterman Award, National Science Foundation, (1992)
Helen B. Warner Prize, American Astronomical Society (1991)
Packard Fellowship in Science and Engineering, (1990)
Presidential Young Investigator, National Science Foundation (1988)

Selected Publications

1. *A Millisecond Pulsar*
Backer, D.C., **Kulkarni, S.R.**, Heiles, C.E., Davis, M.M. & Goss, W.M.,
Nature **300**, 615. (1982)

2. *Optical Identification of Binary Pulsars: Implications for Magnetic Field Decay in Neutron Stars*
Kulkarni, S.R.,
Astrophys. J. **306**, L85. (1986)

3. *Self Noise in Interferometers: Radio and Infrared*
Kulkarni, S.R.
Astron. J. **98**, 112. (1989)

4. *Optical Synthesis Images II: Sensitivity of an* ${}^{n}C_2$ *Interferometer with Bispectrum Imaging*
Kulkarni, S.R., Prasad, S. & Nakajima, T.
J. Opt. Soc. America A **8**, 499 (1990)

5. *Identification of a supernova remnant coincident with the soft* γ*-ray repeater SGR 1806−20*
Kulkarni, S. R. & Frail, D. A.
Nature **365**, 33 (1993)

6. *Discovery of a cool, brown dwarf*
Nakajima, T., Oppenheimer, B. R., **Kulkarni, S. R.**, Golimowski, D. A., et al.
Nature **378**, 463. (1995)

7. *The radio afterglow from the gamma-ray burst of May 8, 1997*
Frail, D. A., **Kulkarni, S. R.**, Nicastro, L., Feroci, M. & Taylor, G. B.
Nature **389**, 261 (1997)

8. *Identification of a host galaxy at redshift z=3.42 for the gamma-ray burst of 14 December 1997*
Kulkarni, S. R., Djorgovski, S. G., Ramaprakash, A. N. et al.
Nature **393**, 35 (1998)

9. *The GRB of 980425 and its association with the extraordinary emission from a most unusual SNe*
Kulkarni, S. R., Frail, D. A., Wieringa et al.,

Nature **395**, 663 (1998)

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1. *Millisecond and Binary Pulsars:*
   E.S.Phinney & S.R.Kulkarni
   Ann. Rev. Astr. Ap., 32, 591–639 (1994)
2. *Tidal Circularization and the Eccentricity of Binaries Containing Giant Stars:*
   F.Verbunt & **E.S.Phinney**
   Astron. & Astrophys., 296, 709–721 (1995)

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1. *The Discovery of an Anomalous X-Ray Pulsar in the Supernova Remnant Kes 73*
   G.Vasisht & E.V.Gotthelf
   Ap. J., 486, L129–L132 (1997)
2. *Identification of PSR1758-23 as a runaway pulsar from the supernova remnant W28*
   D.A.Frail, S.R.Kulkarni & **G.Vasisht**
   Nature, 365, 136–138 (1993)

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PHD, Amsterdam, 1993
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1. *Infrared helium emission lines from Cygnus X-3 suggesting a Wolf-Rayet star companion*
   M.H.van Kerkwijk, P.A.Charles, et al
   Nature 355 703–705 (1992)
2. *The masses of the millisecond pulsar J1012+5307 and its white-dwarf companion*
   M.H.van Kerkwijk, P.Bergeron & S.R.Kulkarni,
   Ap. J., 467, L89–L92 (1996)

Bradley M. S. Hansen

PHD, California Institute of Technology 1996
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1. *Stellar Forensics -II: Millisecond pulsar binaries*
   B.M.S.Hansen & E.S.Phinney
   M.N.R.A.S., 294, 569–581 (1998)
2. *Cooling Models for Old White Dwarfs*
   B.M.S.Hansen
   Ap.J., 520, 680–695 (1999)

REFERENCES

Aannestad, P. A., Kenyon, S. J., Hammond, G. L., and Sion, E. M. 1993, AJ, 105, 1033.

Alcock, C., Fristrom, C. C., and Siegelman, R. 1986, ApJ, 302, 462.

Alcock, C. and Illarionov, A. 1980, ApJ, 235, 534.

Andersson, N., Kokkotas, K. D., and Stergioulas, N. 1999, ApJ, 516, 307.

Andrievsky, S. M. and Paunzen, E. 2000, MNRAS, 313, 547.

Artymowicz, P., Clarke, C., Lubow, S., and Pringle, J. 1991, ApJ, 370, L35.

Bakker, E. J., van der Wolf, F. L. A., Lamers, H. J. G. L. M., Gulliver, A. F., Ferlet, R., and Vidal-Madjar, A. 1996, A&A, 306, 924.

Bartel, N., Chandler, J. F., Ratner, M. I., Shapiro, I. L., Pan, R., and Cappallo, R. J. 1996, AJ, 112, 1690.

Becklin, E. E. and Zuckerman, B. 1988, Nature, 336, 656.

Bell, J. F., Bailes, M., and Bessell, M. S. 1993, Nature, 364, 603.

Bergeron, P., Kidder, K. M., Holberg, J. B., Liebert, J., Wesemael, F., and Saffer, R. A. 1991, ApJ, 372, 267.

Bildsten, L. 1998, ApJ, 501, L89.

Boden, A. F. *et al.* 1999, ApJ, 527, 360.

Brady, P. and Creighton, T. 2000, Physical Review D, 6108, 2001.

Brandt, N. and Podsiadlowski, P. 1995, MNRAS, 274, 461.

Britton, M. C. 2000, ApJ, 532, 1240.

Brown, E. F., Bildsten, L., and Rutledge, R. E. 1998, ApJ, 504, L95.

Brown, G. E. and Bethe, H. A. 1994, ApJ, 423, 659.

Casares, J. and Charles, P. A. 1994, MNRAS, 271, L5.

Casares, J., Charles, P. A., and Naylor, T. 1992, Nature, 355, 614.

Conlon, E. S., Dufton, P. L., Keenan, F. P., McCausland, R. J. H., and Holmgren, D. 1992, ApJ, 400, 273.

Delfosse, X., Forveille, T., Mayor, M., Perrier, C., Naef, D., and Queloz, D. 1998, A&A, 338, L67.

D'Odorico, S., Oosterloo, T., Zwitter, T., and Calvani, M. 1991, Nature, 353, 329.

Dufton, P. L., Keenan, F. P., Kilkenny, D., O'Donoghue, D., Parker, Q. A., van Wyk, F., and van Leeuwen, F. 1998, MNRAS, 297, 565.

Gaudi, B. S. and Sackett, P. D. 2000, ApJ, 528, 56.

Gaume, R. A., Fey, A. L., Boboltz, D. A., and Johnston, K. J. 1999, in Working on the Fringe: An International Conference on Optical and IR Interferometry from Ground and Space, Dana Point, CA, May 24-27, 1999, ed. S. Unwin and R. Stachnik, ASP Conference Series, E59.

Gonzalez, G. and Laws, C. 2000, AJ, 119, 390.

ed. J. B. Hearnshaw and C. D. Scarfe 1999. "Precise Stellar Radial Velocities, IAU Colloquium 170".

Heber, U., Moehler, S., and Groote, D. 1995, A&A, 303, L33.

Herrero, A., Kudritzki, R. P., Gabler, R., Vilchez, J. M., and Gabler, A. 1995, A&A, 297, 556+.

Holman, M. J. and Wiegert, P. A. 1999, AJ, 117, 621.

Jenet, F. A. and Anderson, S. B. 1998, PASP, 110, 1467.

Jenet, F. A., Anderson, S. B., Kaspi, V. M., Prince, T. A., and Unwin, S. C. 1998, ApJ, 498, 365.

Johnson, J. J. *et al.* 1999, MNRAS, 306, 531.

Johnston, H. M. 1992, PhD Thesis, California Inst. of Technology.

Johnston, S. *et al.* 1993, Nature, 361, 613.

Johnston, S., Manchester, R. N., Lyne, A. G., Bailes, M., Kaspi, V. M., Qiao, G., and D'Amico, N. 1992, ApJ, 387, L37.

Kaspi, V. M., Taylor, J. H., and Ryba, M. F. 1994, ApJ, 428, 713.

Kleinman, S. J. *et al.* 1994, ApJ, 436, 875.

Kuijken, K. and Gilmore, G. 1991, ApJ, 367, L9.

Livio, M., Pringle, J. E., and Saffer, R. A. 1992, MNRAS, 257, 15P.

Livio, M. and Soker, N. 1984, MNRAS, 208, 763.

Ma, C. *et al.* 1998, AJ, 116, 516.

Magee, H. R. M. *et al.* 1998, A&A, 338, 85.

Margon, B. 1984, ARA&A, 22, 507.

Mathis, J. S. and Lamers, H. J. G. L. M. 1992, A&A, 259, L39.

Maxted, P. F. L. and Marsh, T. R. 1998, MNRAS, 296, L34.

McClintock, J. E. and Remillard, R. A. 1986, ApJ, 308, 110.

McCook, G. P. and Sion, E. M. 1999, ApJS, 121, 1.

Melatos, A., Johnston, S., and Melrose, D. B. 1995, MNRAS, 275, 381.

Nelemans, G., Tauris, T. M., and van den Heuvel, E. P. J. 1999, A&A, 352, L87.

Nicastro, L., Lyne, A. G., Lorimer, D. R., Harrison, P. A., Bailes, M., and Skidmore, B. D. 1995, MNRAS, 273, L68.

Patterson, R. J., Majewski, S. R., Kundu, A., Kunkel, W. E., Johnston, K. V., Geisler, D. P., Gieren, W., and Muñoz, R. 1999, in American Astronomical Society Meeting, volume 195, 4603.

ed. J. A. Phillips, S. E. Thorsett, and S. R. Kulkarni 1993. "Planets around pulsars; Proceedings of the Conference, California Inst. of Technology, Pasadena, Apr. 30-May 1, 1992".

Rasio, F. A., Tout, C. A., Lubow, S. H., and Livio, M. 1996, ApJ, 470, 1187.

Rolleston, W. R. J., Hambly, N. C., Keenan, F. P., Dufton, P. L., and Saffer, R. A. 1999, A&A, 347, 69.

Sackmann, I. ., Boothroyd, A. I., and Kraemer, K. E. 1993, ApJ, 418, 457+.

Saffer, R. A., Keenan, F. P., Hambly, N. C., Dufton, P. L., and Liebert, J. 1997, ApJ, 491, 172.

Sandhu, J. S., Bailes, M., Manchester, R. N., Navarro, J., Kulkarni, S. R., and Anderson, S. B. 1997, ApJ, 478, L95.

Segretain, L., Chabrier, G., and Mochkovitch, R. 1997, ApJ, 481, 355.

Shahbaz, T., Ringwald, F. A., Bunn, J. C., Naylor, T., Charles, P. A., and Casares, J. 1994, MNRAS, 271, L10.

Siess, L. and Livio, M. 1999, MNRAS, 304, 925.

Tauris, T. M., Fender, R. P., van den Heuvel, E. P. J., Johnston, H. M., and Wu, K. 1999, MNRAS, 310, 1165.

Thorsett, S. E. and Chakrabarty, D. 1999, ApJ, 512, 288.

Timmes, F. X., Woosley, S. E., and Weaver, T. A. 1996, ApJ, 457, 834.

Turcotte, S. and Charbonneau, P. 1993, ApJ, 413, 376.

Turyshev, S. G. 1999, in Working on the Fringe: An International Conference on Optical and IR Interferometry from Ground and Space, Dana Point, CA, May 24-27, 1999. Proceedings to be published in ASP Conference Series (S. Unwin and R. Stachnik, editors), p. 69., ed. S. Unwin and R. Stachnik, E69.

van den Heuvel, E. P. J. and van Paradijs, J. 1997, ApJ, 483, 399.

van Kerkwijk, M. H. V. K. 2000, astro-ph/0001077.

van Paradijs, J. and White, N. 1995, ApJ, 447, L33.

Van Winckel, H., Mathis, J. S., and Waelkens, C. 1992, Nature, 356, 500+.

Van Winckel, H., Waelkens, C., and Waters, L. B. F. M. 1995, A&A, 293, L25.

Venn, K. A. and Lambert, D. L. 1990, ApJ, 363, 234.

Vennes, S. . 1999, ApJ, 525, 995.

Verbunt, F. 1993, ARA&A, 31, 93.

Verbunt, F. and Phinney, E. S. 1995, A&A, 296, 709.

Waters, L. B. F. M. *et al.* 1998, Nature, 391, 868.

Waters, L. B. F. M. *et al.* 1989, A&A, 211, 208.

Waters, L. B. F. M., Trams, N. R., and Waelkens, C. 1992, A&A, 262, L37.

White, R. L. *et al.* 2000, ApJS, 126, 133.

Wolszczan, A. and Frail, D. A. 1992, Nature, 355, 145.

Zuckerman, B. and Reid, I. N. 1998, ApJ, 505, L143.