CROWDED-FIELD ASTROMETRY AND IMAGING
with the
SPACE INTERFEROMETRY MISSION

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Executive Summary

The Space Interferometry Mission will be the first space astrophysics instrument to provide a capability for synthesis imaging at optical wavelengths, offering the promise of imaging high-surface-brightness targets with more than 4 times the best resolution attainable with the Advanced Camera on the Hubble Space Telescope. SIM may also provide a nulling-imaging capability for characterizing faint extended emission around a bright star. However, the full details of these capabilities remain to be defined, and the Imaging and Nulling Scientist on the SIM Science Team will play an important role in that effort over the coming several years. The Principal Investigator (PI) on this proposal is applying for that crucial Mission Scientist position.

Since SIM science proposals which would require nulling and/or full coverage of the aperture plane are being delayed, this proposal describes a program of astrometric measurements (positions and proper motions) on crowded star fields in the cores of globular clusters and in the nucleus of the nearby galaxy M 31. These observations will permit accurate values and limits to be placed on the masses of the black holes which are thought to be lurking in these regions of enormously high stellar density. The science can be accomplished even if an imaging capability with a complete set of baselines can not be provided with SIM. The observing program requires repeated synthesis imaging observations of each target field, once annually, over the 5-year lifetime of the mission. The target list described here is not meant to be all-inclusive, but only representative of those objects for which the general science goals described above may be achieved. The program can be carried out in the ≈ 50 hours/yr of mission time allocated to the Imaging and Nulling Mission Scientist.

The proposal also describes how the Principal Investigator plans on carrying out the tasks and responsibilities of the Imaging and Nulling Mission Scientist. Important parts of that task will be, in the first few years, to act as an expert resource for the JPL SIM Project on the subject of synthesis imaging, to continue to be an advocate for providing a full imaging and nulling-imaging capability on SIM, to educate the astronomical community on the results which may be obtained if that capability is available, and to feed this experience into other NASA missions. The proposal includes Co-Investigators who will assist the Imaging and Nulling Mission Scientist for the duration of the project, and who will collaborate on the specific SIM science investigation proposed here.

1 Science Investigation and Technical Description

1.1 Relation to the SIM AO

The Announcement of Opportunity to which this proposal is responding lists three "Key Technology Requirements" for the Space Interferometry Mission (AO 00-OSS-01, Page 4, Table 2). The first requirement, "Use of Interferometry Techniques", encapsulates the fundamental design goals for the SIM spacecraft; these goals must be met if SIM is to carry out its primary astrometric science program. The present proposal is primarily directed at the second and third technology requirements, "Demonstration of Synthesis Imaging", and "Demonstration of Starlight Nulling". However, at this early date in the mission design, there is some uncertainty as to whether SIM will be able to provide the full range of baselines required to achieve quantitatively-accurate imaging of arbitrarily-complex targets. Similarly there is also uncertainty about the ability to provide nulling on every baseline.[1] For these reasons, the AO states that **"...proposals whose primary science goals are imaging or nulling measurements are NOT being solicited through this AO."** The present proposal therefore describes unique science projects which SIM can undertake in the category of ***astrometry in crowded fields*** (the AO explicitly states that such proposals are appropriate, cf. Section 2.2 of the AO, page 5). The data processing and analysis techniques used in synthesis imaging are still required in order to accomplish the science, but the fields are generally less complicated and consist of a modest number (< 50) of (generally point) sources (stars) within the $\approx 1.4''$ SIM field of view. The SIM project has not yet developed detailed timelines for synthesis imaging. It is expected that the data acquisition will most closely resemble the narrow-angle scenario as described on the SIM AO Support web site, using one or two reference stars, without cycling; however, the details have not yet been worked out. For this reason we do not present detailed timelines for the targets listed in this proposal. We estimate only ***the on-target observing times and the number of (u,v) points*** required to achieve our science objectives. For the purposes of establishing whether our program can fit into the ~ 50 mission hours per year to be allocated to the Mission Scientist positions, we conservatively assume an overhead of 100% (i.e., 25 available hours per year of total on-target integration time).

1.2 Merits of a crowded-field astrometry program

The general goals and objectives of astrometry in crowded star fields is the same as on isolated stars, namely, to measure as accurately as possible the positions and proper motions of the stars. Unfortunately, attaining the highest astrometric accuracy of SIM requires that the stars are isolated, and special techniques of observation and data analysis will be required in crowded fields. However, some of the most interesting environments in astrophysics involve crowded stellar fields. For example, the central regions of many galaxies apparently harbor

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[1] Examples of the full range of science which would be enabled by removing these restrictions is described e.g. in Chapter 6 of the SIM Science Requirements Document (SRD). The PI of this proposal was the lead author of that chapter entitled "Synthesis Imaging and Nulling-Imaging Requirements". Proposals aimed at those science goals will be submitted at a later date if the opportunity to do so is made available.

black holes, and these objects appear to be more massive in the larger, more evolved galaxies. The study of these central regions in galaxies can therefore contribute to an understanding of galaxy evolution with time, thereby providing a link to the first scientific goal in NASA's "Origins" theme: **" To understand how galaxies formed in the early universe and to determine the role of galaxies in the appearance of planetary systems and life."**

Future large space telescopes which are being planned to support the Origins theme such as the Terrestrial Planet Finder and the Planet Imager must employ synthesis imaging techniques in the near-infrared and visible regions of the spectrum in order to achieve the necessary angular resolution. Our program of crowded-field astrometry with SIM will require that we utilize and develop these synthesis imaging techniques at optical wavelengths in order to accomplish our science goals. SIM will be the first instrument to offer this capability, and therefore our proposal will also contribute as a technological pathfinder to support future space missions in the Origins theme.

1.3 Stellar motions and black holes in the nuclei of nearby galaxies

Observational evidence for massive dark objects (MDOs) in galactic nuclei has been gathered for more than two decades. The MDO is commonly assumed to be a supermassive black hole (BH), but only in a few cases have plausible alternatives to an BH been ruled out. Recently, the focus has changed from individual galaxies to demographic studies (see, e.g., Richstone et al. 1998 for a recent review). The current paradigm holds that BHs are common in galaxy nuclei, and that their masses scale ∼linearly with the bulge mass of the host galaxy.

Observational constraints on the presence of BHs in galaxies can be derived either from stellar or gas kinematics. The most compelling evidence so far was obtained from stellar proper motions in the Milky Way galaxy (Eckart & Genzel 1997; Ghez et al. 1998), and water maser gas in NGC 4258 (Miyoshi et al. 1995). In general, stars are better suited for probing the gravitational potential than viscous gaseous matter, because they can be considered collisionless test particles in most cases. However, stellar motions are also extremely difficult to trace observationally, because of the small angular scales involved. While stellar dynamical evidence for MDOs has been obtained for several galaxies from integrated light measurements with the Hubble Space Telescope (HST; e.g., van der Marel et al. 1997a), the Milky Way is the only case in which stellar proper motions have been directly observed. These observations have essentially ruled out alternatives to a single BH in the center of the Milky Way.

The unprecedented astrometric accuracy of SIM offers the unique opportunity to measure for the first time the stellar proper motions in the nuclei of external galaxies. Multi-baseline imaging measurements with SIM can yield a resolution of about 8 milliarcseconds (mas) at 600 nm. However, the quality of the restored images is not easily predictable because their signal-to-noise ratio depends on many parameters, the most important ones being the (u,v)-coverage and the structure of the source. Therefore, detailed modeling for each individual target is required to optimize the observing strategy and to predict the quality of the reconstruction.

For these reasons, we have developed imSIM, a software package to simulate the synthesis

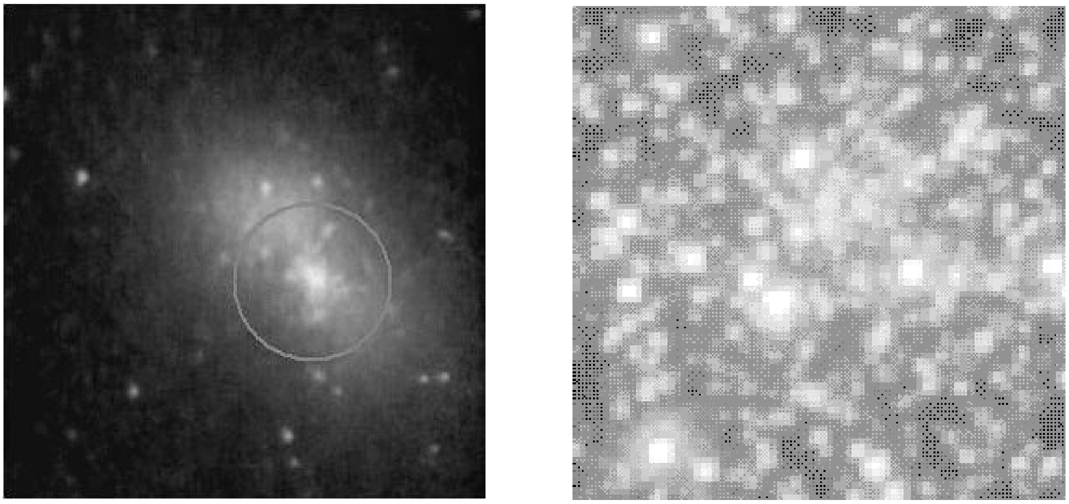

Figure 1: HST images of our two highest priority targets. a) The central 3.5″ of M 31 in a greyscale representation that emphasizes B-band and UV light (Brown et al. 1998). The circle denotes a 1.2″ diameter aperture, close to the expected SIM field of view. The SIM imaging-mode resolution will be ≈ 0.7% of the size of the circle. b) The nuclear region of the globular cluster M 15 at the same scale as the left panel (Guhathakurta et al. 1996). The adopted stretch only slows the brighter stars ($V \lesssim 17$); the proposed SIM data will yield proper motions for stars as faint as $V = 21$–22.

imaging mode of SIM (Böker & Allen 1999). We have used imSIM to demonstrate the feasibility of proper motion studies of nuclear star clusters in external galaxies.

1.3.1 The Andromeda Galaxy

The Andromeda Galaxy (M 31) is the nearest giant spiral galaxy, and its nucleus can therefore be studied at higher resolution than for any comparable galaxy. Interestingly, the sub-arcsec nuclear structure of M 31 has turned out be a considerable puzzle, which indicates that there remains much to be learned about galactic nuclei in general. HST images of M 31 have revealed a double nucleus (Lauer et al. 1993). Integrated light spectroscopy of absorption features from the ground and with HST indicate that one of the two nuclei hosts an MDO of $\approx 3 \times 10^7\,\mathrm{M}_\odot$ (e.g., Kormendy & Bender 1999; Statler et al. 1999). This nucleus is bluer than its surroundings and contains UV-bright stars with apparent magnitudes up to $m_V \approx 21$. It is hence believed to be a young star cluster surrounding a BH (Brown et al. 1998; Lauer et al. 1998). The second nucleus has been postulated to be the result of crowding of stars at the apocenters of their orbits in an eccentric disk (Tremaine 1995).

We expect that SIM measurements of stellar proper motions will for the first time provide a detailed understanding of the nuclear structure of M 31. Fig. 1a shows a greyscale image of the central 3.5″ from Brown et al. (1998), with the SIM field-of-view superposed. The observed line-of-sight velocity dispersion at the position of the central star cluster, measured at the ≈ 0.1″ resolution of HST, is $\sigma = 440\ \mathrm{km\,s^{-1}}$ (Statler et al. 1999). The velocity dispersion in the plane of the sky is a factor of $\sqrt{2}$ larger, which — at the M 31 distance of

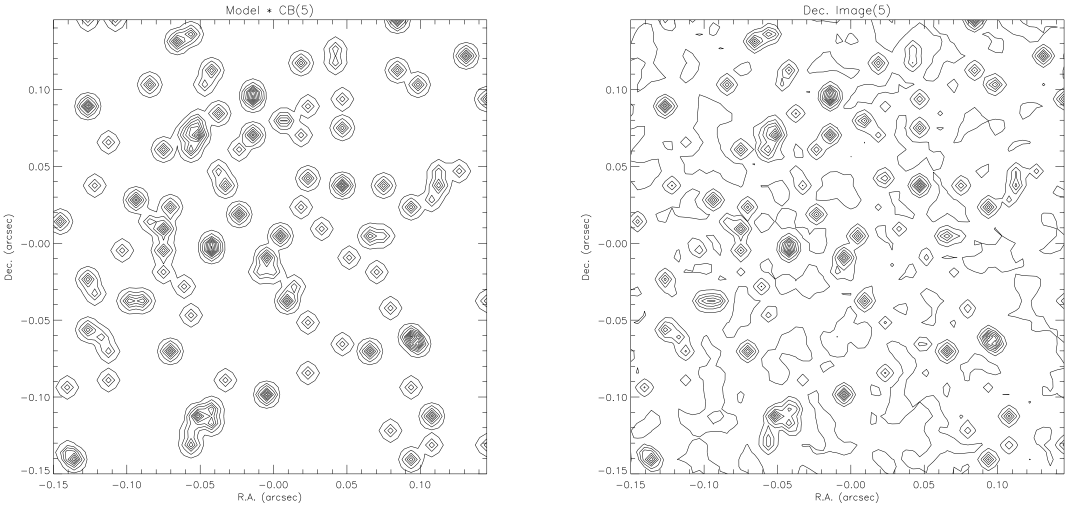

Figure 2: a) input source model for the nuclear star cluster in M 31. The stars in this simulation range from 21 to 23 mag in V. b) reconstructed image after 1200 CLEAN iterations. The simulation used the (u,v)-coverage shown in Fig. 3a, with a total on-source integration time of 4 h.

770 kpc — corresponds to about 0.8 mas proper motion over the SIM mission lifetime of five years. This is equivalent to 10% of the SIM beam width, and our simulations presented below demonstrate that this is easily measurable in synthesis images with SIM. Moreover, the velocity dispersion around a BH increases towards the center as $1/\sqrt{r}$, and should therefore correspond to several mas of proper motion over the SIM mission lifetime at the SIM resolution limit. And finally, about 30% of the stars will have velocities larger than σ, because of the Maxwellian velocity distribution. So this is clearly a feasible experiment.

1.3.2 Crowded field astrometric imaging simulations

Our input source model of the nuclear cluster in M 31 for the simulations is constructed as follows. The surface brightness within $r = 0.15''$ is $\approx$ 13.7 mag/arcsec^2 in V (Lauer et al. 1998). We assume a SIM throughput of 33% and interferometer elements of 30 cm diameter, and model the central $0.3''$ of the SIM field of view. We have constructed a population of stars with a luminosity function according to the Salpeter (1955) initial mass function (IMF). We conservatively assume a uniform background surface brightness of $\mu_V =$ 15.5 on which we superpose stars drawn from the luminosity function with a random spatial distribution until the surface brightness observed by Lauer et al. (1998) is reached. The source model is calculated in five channel maps of 100nm width between 500nm and 1000nm. We assume blackbody spectra for the stars according to their spectral type. The first channel map (roughly corresponding to V-band) of the source model is shown in Fig. 2.

The complex visibilities at the (u,v)-coordinates for 150 baselines shown in Fig. 3a are then measured separately for each channel, and combined in a spectral synthesis mode to improve (u,v)-coverage. The details of the simulated measurement process are described in Böker & Allen (1999). The choice of 150 baselines is motivated as follows: the simulation in Fig.

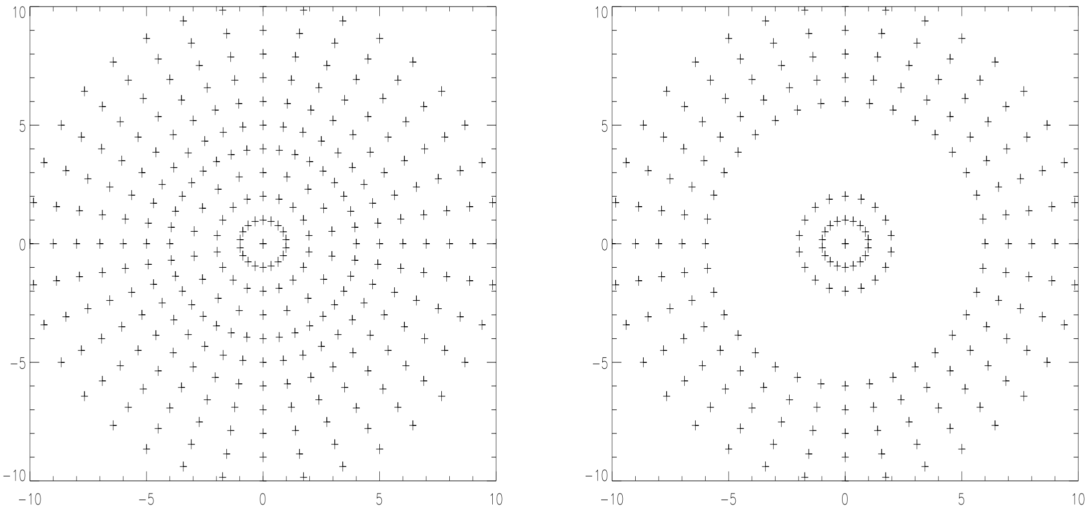

Figure 3: Assumed SIM baseline distribution. The longest baseline is 10 m, the shortest baseline is 1 m, and the increment is 1 m. a) distribution with all SIM siderostats. b) available distribution after loss of the siderostat at (+1 m).

2a indicates that we may expect to find $\approx$ 50 stars in a field of view $0.3''$ in diameter. Very roughly, such a field requires about 50 independent complex visibility measurements to represent it. However, there may be more stars present, and the SIM field stop is likely to be larger than $0.3''$, so we have conservatively increased the number of (u,v) points required by a factor of 3. The final value will be chosen when the SIM field stop size is fixed.

The reconstructed image after 1200 iterations of the CLEAN algorithm is shown in Fig. 2b (for a total on-source integration time of 4 h). The CLEAN residuals have been added back into the image to demonstrate the fidelity of the reconstruction. In order to investigate whether the expected proper motion of individual stars can be measured against the image residuals, we have plotted reconstructed images of stars with $V = 21$ and $V = 22$ in Fig. 4. In each case, a second reconstruction has been overplotted with the star shifted by 1 mas. As can be seen in Fig. 4, differencing the two reconstructions clearly reveals the S-shaped signature of the stellar motion. The comparison to a noiseless model (dotted line) demonstrates the high fidelity of the reconstruction. From simple Gauss-fitting to the stellar profile, we determine that the centroid can be determined to 0.25 mas for the brightest stars.

The success of the M 31 program will depend on the magnitude of the individual stars, a quantity that is not well constrained even from the best available data. V-band magnitudes of $M_V = -3.5$ (corresponding to $m_V = 21$ at the distance of M 31) are typical for bright giants (Luminosity Class II) around spectral type A0. If the cluster is very young, it could contain supergiant stars which are brighter than $M_V = -3.5$. It should be noted, however, that the relatively smooth surface brightness distribution found in the HST WFPC2 images of Lauer et al. (1998) is not very supportive of this possibility, because much brighter stars would stand out above the background.

Note that this project is feasible even if the SIM (u,v)-coverage is reduced. The baseline

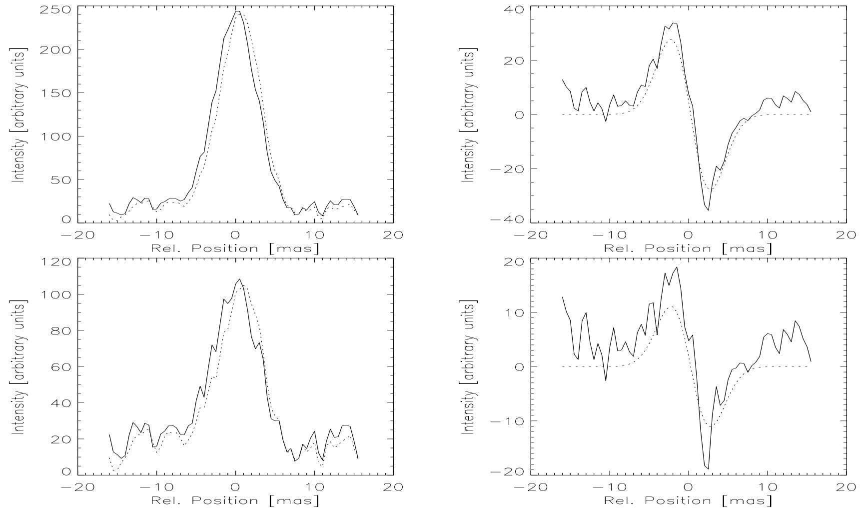

Figure 4: Top left: two reconstructed images of a star with $V = 21$, separated by 1 mas. Top right: difference between the two reconstructions (solid line), compared to a noiseless model (dotted line). Bottom: same as above, for a star with $V = 22$.

distribution shown in Fig. 3b is that available after a failure of the least redundant siderostat[2]. We have determined that in this case, with the same integration time as used for the full (u,v)-coverage, the centroiding accuracy will be degraded by about a factor of 2, to 0.5 mas. This is still sufficient to detect the expected proper motions in the nucleus of M 31 (cf. Section 1.3.1).

Our simulations include photon statistics, but no instrumental imperfections. In particular, the noise distribution does not account for possible systematic calibration errors of the interferometer, which will degrade the accuracy of the fringe phase and amplitude measurements. The latest version of IMSIM has the ability to incorporate various models for the distribution of such instrumental errors when they become available.

1.3.3 Other candidate galaxies in the Local Group

We have looked at several other Local Group galaxies as possible targets, in particular M 32 and NGC 205 (the companions of M 31), and M 33. The latter two galaxies have rather low central velocity dispersions, $\sigma \lesssim 50 \mathrm{km\,s^{-1}}$, as measured from ground-based data. This places stringent limits on the possible presence of a BH, $M_{\mathrm{BH}} \lesssim 10^5\ \mathrm{M_\odot}$ (Held 1990; Kormendy & McClure 1993; Jones et al. 1996). If they do have a BH (with mass below this limit), then the velocities would obviously increase towards the center. However, in its aperture synthesis mode for crowded fields SIM can only measure velocities in excess of $\approx 250\ \mathrm{km\,s^{-1}}$ (0.5 mas proper motion over five years, at 0.8 Mpc distance). Such velocities are not reached for NGC 205 and M 33 at distances from the center that can be resolved with SIM. By contrast, the galaxy M 32 does have a relatively high central velocity dispersion ($\sigma \approx 150\ \mathrm{km\,s^{-1}}$ at

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[2] The siderostat placement assumed for these simulations is at positions (−5 m), (−4 m), (−3 m), (+1 m), (+3 m), (+4 m), and (+5 m), measured from the middle of the truss. This provides all spacings 0 to 10 m in steps of 1 m.

HST resolution; van der Marel et al. 1997b), and an inferred MDO of mass 3×10^6 $\mathrm{M}_\odot$. However, it has a predominantly old stellar population, and there is no reason to expect bright young stars that can be resolved and imaged by SIM, as is the case for M 31.

Based on these arguments, we think that M 31 provides the only galaxy nucleus for which proper motion measurements are feasible with SIM. Nevertheless, high-dynamic range images of the enigmatic stellar cores of the nearby Local Group galaxies could be very interesting by themselves. For example, the nucleus of the Scd galaxy M 33 is the most X-ray luminous of the Local Group galaxies, and it is also extremely compact. The core radius is only 0.39 pc, as small or smaller than core-collapsed globular clusters (Kormendy & McClure 1993). It is far from obvious how such a dense core in an otherwise flat gravitational potential (M 33 basically has no bulge) could have formed. The elliptical galaxy M 32 has a stellar density that increases inward to densities that are higher than those observed in any other galaxy nucleus (Lauer et al. 1992). It would be very interesting to know whether this trend is continued down to the SIM resolution limit, as predicted by models for a stellar distribution around a central BH (van der Marel 1999). So while we do not apply in the current proposal for observations of Local Group targets other than M 31, we might do so at a later stage when SIM imaging proposals are solicited.

1.4 Stellar kinematics in the cores of globular clusters

Globular clusters could harbor massive central BHs just as galaxies do. In galaxies the BH often directly reveals itself through its associated accretion and activity, and the galaxy is identified as an AGN or quasar. While such activity is never observed in globular clusters, it may well be that (some) globular clusters also contain BHs. There are many ways in which globular cluster evolution at high densities (Meylan & Heggie 1997) can lead to the formation of a massive BH in the center (Rees 1984). For example, core collapse induced by two-body relaxation may lead to sufficiently high densities for individual stars or stellar-mass black holes to interact or collide, with a single massive BH as the likely end product (Quinlan & Shapiro 1987; Lee 1993, 1995).

The black hole mass $M_\bullet$ in galaxies correlates with galaxy (bulge) mass M such that $M_\bullet/M \approx 10^{-3\pm1}$ (Magorrian et al. 1998; van der Marel 1999). One may use this correlation to obtain a crude estimate for the possible BH masses in globular clusters (although it should be kept in mind that the BHs in galaxies may have formed in very different fashion). This yields $M_\bullet \approx 10^3 M_\odot$.

So far, no unambiguous detection of a massive BH has been reported for any globular cluster. However, this is not necessarily a very meaningful result, for two reasons. First, only few globular clusters have been studied in enough detail to place any meaningful limits on the presence of BH. Second, for those clusters that were studied in detail, the spatial resolution of the observations was such that only BHs more massive than $M_\bullet \gtrsim 10^{3.5-4} M_\odot$ could have been confidently detected. By contrast, proper motion measurements with SIM will be able to detect BHs that are at least a factor of 10 less massive than this. This will for the first time probe the region of BH mass parameter space that is of physical interest.

Our highest priority target is the globular cluster M 15 (NGC 7078) at a distance of 10 kpc.

An HST image of the central region is shown in Fig. 1(b). We discuss this cluster in detail; the selection of additional target clusters for our program is discussed in Section 1.4.2.

1.4.1 The core-collapsed cluster M 15

M 15 is one of the densest globular clusters in our Galaxy, and it has the highest observed central surface brightness (Harris 1996). The presence of a bright X-ray source (Hut et al. 1992) and several millisecond pulsars (Phinney 1993) are manifestations of its extreme density, which makes M 15 one of the best a priori candidates to search for evidence of a central BH. For this reason, M 15 has been intensively observed in the past decade using a variety of techniques, and it is also the subject of several ongoing studies (as reviewed in van der Marel 2000). This makes M 15 the natural choice as our highest priority target.

M 15 is a proto-typical 'core-collapsed' cluster (Djorgovski & King 1986). Such clusters have stellar surface density profiles that rise all the way into the center. They make up $\sim 20\%$ of all globular clusters in our Galaxy, and stand in marked contrast to King-model clusters, which show flat central cores and are modeled as tidally-truncated isothermal systems. HST imaging studies of M 15 (Guhathakurta et al. 1996; and Sosin & King 1997) found that the projected stellar surface number density profile near the center is well represented by a power law $N(R) \propto R^{-0.7\pm0.1}$. This is consistent with the predictions of models for the equilibrium stellar density distribution around a BH (Bahcall & Wolf 1976), but can be fit equally well with core-collapse models (Grabhorn et al. 1992). Kinematical studies are therefore essential to gain further insight.

M 15 has been the subject of many ground-based kinematical studies. Observational strategies have focused primarily on the determination of velocities of individual stars, using either spectroscopy with single apertures, long-slits or fibers (e.g., Drukier et al. 1998), or using imaging Fabry-Perot spectrophotometry (e.g., Gebhardt et al. 2000). Integrated light measurements using single apertures have also been attempted, but have been shown to be of limited use (Dubath, Meylan & Mayor 1994). Line-of-sight velocities are now known for ~ 1800 M 15 stars, as compiled by Gebhardt et al. (2000). The projected velocity dispersion profile inferred from this sample is shown in Fig. 5. It increases monotonically inwards from $\sigma = 3 \pm 1$ km/s at $R = 7$ arcmin, to $\sigma = 11 \pm 1$ km/s at $R = 24''$. The velocity dispersion is approximately constant at smaller radii, and is $\sigma = 12 \pm 3$ km/s at the innermost available radius $R \approx 1''$ (Gebhardt et al. 2000). The figure also shows the predictions of spherical dynamical models for M 15 in which the velocity distribution is isotropic and the stellar population has a mass-to-light ratio $M/L = 1.7$ (in the V-band) that is independent of radius. Different curves correspond to different BH masses. A BH causes the velocity dispersion to rise in Keplerian fashion as $\sigma \propto R^{-1/2}$ towards the center of the cluster. The best-fitting model of this type has $M_\bullet \approx 2000 M_\odot$. However, it should be noted that the data can be fit equally well with a model in which the M/L of the stellar population increases inwards to a value of $M/L \approx 3$ in the center (not implausible, since mass segregation would tend to concentrate heavy dark remnants to the cluster center). And finally, it is also possible to fit the data with a model in which M/L is constant throughout, but in which the three-dimensional stellar velocity dispersion is somewhat anisotropic.

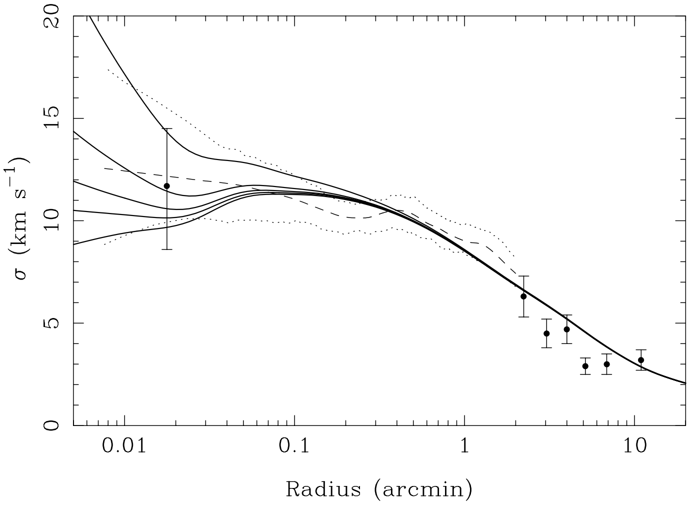

Figure 5: Projected velocity dispersion profile of M 15 from ground-based data (Gebhardt et al. 2000). Binned data are shown as dots with error bars, while a non-parametric estimate of the dispersion profile in the central arcmin is shown as a dashed line bounded by two dotted lines (the latter representing the 68.3% confidence region). Solid curves are predictions of isotropic models with BHs that have $M_\bullet = 0, 500, 1000, 2000$, and $6000 M_\odot$, respectively. The proposed SIM data will yield the velocity dispersion 10 times closer to the center ($0.1'' = 0.0017$ arcmin) than the ground-based data.

There are only 5 stars in the central arcsec with known velocities. So it is not possible to determine the velocity dispersion close enough to the center to discriminate between the various models of physical interest, which only give significantly different predictions at radii of order $0.1''$ (see Fig. 5). To make further progress, it is of crucial importance to obtain more stellar velocities close to the center. Velocity determinations at $R \lesssim 2''$ are very difficult due to severe crowding and the presence of a few bright giants in the central arcsec. Adaptive optics observations have been attempted (Gebhardt et al. 2000) but despite the small $0.09''$ FWHM did not yield many new velocities because of the low Strehl ratio (the PSF wings of bright giants drown out fainter stars). Studies with HST are also underway, but are unlikely to improve the situation. The problem for spectroscopy (van der Marel et al. Cycle 8) is that stars near the main-sequence turn-off are too faint to get reliable spectra. The problem for imaging studies (van Altena et al. Cycle 7) is that the HST PSF causes blending of stars in the central arcsec, thus making it impossible to centroid stars to the necessary accuracy (of order 0.5 mas; i.e., 1% of the HST PSF) for proper motion determination.

SIM is the only instrument that will allow significant progress to be made on this subject within the next decade. As discussed in Section 1.3.2, we expect to be able to confidently measure proper motions as small as 0.5 mas over a 5 year baseline, for stars with magnitudes as faint as $V = 21$. At the 10 kpc distance of M 15 this corresponds to a velocity of 5 km/s. The line-of-sight velocity dispersion near the center of M 15 observed at ground-based resolution is $\sigma = 12$ km/s, so the corresponding proper motion dispersion is $\sigma = 17$ km/s (larger by $\sqrt{2}$). Hence, all stars that are bright enough to be detected will be observed to move over the 5 year baseline. The main-sequence turn-off is at $V = 18.5$, which is well within the reach of SIM. However, to obtain a sufficient number of stars within the SIM field of view to measure a reliable velocity dispersion we need to go fainter than this. Extrapolation of the radial number density profile and luminoisty function measured with HST to small radii indicates that we should expect of order 50 stars with $V \leq 21$ at distances $R \leq 0.2''$ from the center (and many more in the entire SIM imaging FOV). This is small enough that crowding is not a problem (given the ≈ 10 mas resolution of SIM) and large enough to accurately measure the velocity dispersion at an average radius of $R = 0.1''$. This is 10 times closer to the center than the velocity dispersion is currently known, and will allow us to place strong constraints on the mass-to-light ratio variations with radius in M 15, and will detect any BH with mass $M_\bullet \gtrsim 10^{2.5} M_\odot$, if present. We note also that the central escape velocity of M 15 in the absence of a BH is expected to be ~ 40 km/s (e.g., Webbink 1985); any (non-binary) stars found to have velocities exceeding this value will provide additional and independent evidence for a central mass concentration.

1.4.2 Target list

To complete our target list we considered only core-collapsed globular clusters. These are the only clusters where the central densities are high enough to suggest that proper motion studies may reveal something of physical interest (a BH, or least strong mass segragation). At the same time, the high central densities in these clusters lead to severe crowding, which prevents proper motion measurements with any instrument other than SIM. We selected all core-collapsed globular clusters from the catalog of Milky-Way clusters compiled by Harris (1996). M 15 is the cluster with the highest average central surface brightness (14.2 mag/arcsec^2 in V, at $1''$ from the center) in the resulting list. There are eight other clusters for which the central surface brightness is within 1.5 mag of that for M 15. They are (in order of decreasing central surface brightness): NGC 362, NGC 6752, NGC 7099 (M 30), NGC 6681 (M 70), NGC 6266 (M 62), NGC 6624, NGC 6541 and NGC 6397. These clusters are all less massive than M 15, and their intrinsic velocity dispersions are lower than for M 15 by up to a factor 3. On the other hand, all eight clusters are closer than M 15 (distances between 2.3 and 9 kpc), so that the proper motions should be very similar as for M 15. We will select our final target list after the observational characteristics of SIM have been better established. If the proposal is approved, we will also start ground-based radial velocity studies of these clusters which will allow us to select the most optimal targets for the SIM observations.

1.5 Observing time requirements

For the reasons outlined in Section 1.1, we do not quote a very detailed break-down of our observing time requirements. However, our simulations of Section 1.3.2 show that ≈ 4 hours of on-source integration time are sufficient to yield positions accurate to ≈ 0.5 mas for all stars in a field brighter than $V = 21$–22. Our current plan is to obtain at least one such "snapshot" image per year, for each target. Assuming 25 hours of available on-source integration time per year (cf. Section 1.1), this allows us to study 6 targets in our project. We will certainly study M 31 and M 15, to which we will add four of the globular clusters listed in Section 1.4.2 (to be selected later).

Our sampling strategy of observing each target (at least) once per year has several benefits: (1) it will increase the accuracy of the proper motion measurements; (2) it will provide a handle on systematic effects over the mission lifetime; and (3) it may allow us to measure any deviations from linear motion which yield the stellar accelerations. It should be pointed out that for each image, the complex visibilities for all available baselines should be measured over a relatively short period of time in order to avoid smearing due to the stellar motions. We consider a time span of 1 month as sufficient, because the expected proper motions over one month are $\lesssim 0.05$ mas. This is only about 10% of the optimal positional accuracy, and can thus be neglected.

1.6 Conclusions

Through the proposal described here, SIM will permit us to make unique contributions to the study of very dense stellar environments, and at the same time advance our knowledge of interferometric synthesis imaging techniques in space. We will learn more about the origin and evolution of the enigmatic black holes which live in the central regions of many galaxies, and therefore more about the origin and evolution of the galaxies themselves. Finally, this grand endeavour with SIM will help to prepare us technologically for the next generation of space interferometers in the Origins theme, the Terrestrial Planet Finder and the Planet Imager.

2 Education/Public Outreach Participation

The PI is eager to participate in Education and Public Outreach activities as outlined in the AO, including, **"...developing ideas for creative and worthwhile educational materials; preparing written background information suitable for primary and secondary school educational resources; and/or preparing portions of their mission's data for use in educational and public outreach materials."**

The PI's home institution is a particularly good location for E/PO activities, since the STScI Office of Public Outreach (OPO) is explicitly tasked by NASA to coordinate the education and public outreach efforts of all NASA missions within the Origins theme, and carries out this mandate in its Origins Education Forum Program. In addition, OPO at STScI has a well developed K-12 Curriculum Program, an Informal Science Education Program for the general public, a directed Public Information and Outreach Program for materials derived from the Hubble Space Telescope, and a News Program which develops press and photo releases for PIs and assists NASA with its regular Space Science Updates, among other activities. These resources can be made available to the PI for E/PO activities related to SIM.

It should be noted that imaging with SIM is likely to be one of the first and most effective ways in which the SIM Science Team and the SIM Project Office will be able to show the public that SIM is operating successfully, even at a very early stage in the mission, and well before any significant astrometric results are available. The PI expects to assist the Science Team with the development of a program of Early Release Observations which will include suitable imaging targets.

4 Roles and Responsibilities as a Mission Scientist

The major responsibility of the Imaging and Nulling Mission Scientist is to ensure that SIM meets the second and third "Key Technology Requirements" (AO 00-OSS-01, Page 4, Table 2): "Demonstration of Synthesis Imaging", and "Demonstration of Starlight Nulling". This section describes how the PI will address these technology requirements in the coming years.

4.1 Demonstration of synthesis imaging

According to the Mission Operations section on the SIM AO Support web site, the SIM project is presently expecting to deliver astrometric data products to Level 4 (Astrometric data with Special and General Relativistic signatures removed) through the Interferometer Science Center (ISC). Such data is adequate to demonstrate synthesis imaging with SIM, even if the data at various (u,v) points on a given target are collected over an extended time interval.

Images can be made with any number of data points in the (u,v) plane; indeed, an image can be made from a single complex visibility. However, such an image would in general look like a plowed field viewed from above, and would probably be considered neither as very satisfactory nor very useful. How many (u,v) points are needed as input data in order to satisfy the second Key Technology Requirement in the AO? The requirement states that the coverage should be **"...adequate to image up to 50 point sources located within the $\sim 1''$ (arc-sec) primary beam of a single telescope, e.g., for imaging the core of a globular cluster."** Fourier theory (and the sampling theorem) tells us that to image this many point sources will require approximately 50 complex visibility measurements over the (u,v) plane, each taken with a separation of $\geq d/\lambda$ from its nearest neighbor, where d is the diameter of a siderostat.

The ISC is currently not tasked with providing software and support for imaging with SIM (also a Level 4 data product). The PI and his colleagues are developing computer software which can process any number of SIM (u,v) data points into an image (Böker & Allen 1999). An early release of this software (the "IMSIM" simulator) is presently available to the community on a workstation at JPL, and more capable versions are under development at STScI. The latest version of IMSIM has been used to model Galactic globular cluster targets and the core of the galaxy M 31, as described in Section 1.3.2 of this proposal.

With the experience we already have on our team, and the software tools we have created and are constantly improving, we are confident that we have the ability to determine whether SIM will meet its second technology goal of demonstrating synthesis imaging.

4.1.1 Covering the (u,v) plane

For the purpose of meeting the second technology goal as described in the AO, no demands need to be put upon the (u,v) coverage other than the rather loose requirement on the minimum spacing between (u,v) points as described in the previous section. This means that the coverage in the (u,v) plane may be quite non-uniform and still be acceptable. However, the images produced from such incomplete data will suffer from a variety of imperfections and may even be quite unreliable for quantitative measurements. We have used our IMSIM simulator on several occasions to show the deleterious effects of inadequate (u,v) coverage. It will be an important task of the Imaging and Nulling Mission Scientist to provide input to the SIM Project on this crucial point; the science return from SIM will be significantly enhanced if a full and regular set of interferometer baselines can be provided.

4.1.2 Time line and observing efficiency for imaging

The JPL SIM Project has developed time lines for narrow- and wide-angle astrometric measurements with SIM; however, no time lines have been presented for imaging (even for the more limited goals of crowded-field astrometry). The astrometric time lines presented have a significant amount of overhead, such that the actual time spent gathering photons from a science target is a small fraction of the "wall clock" time. These time lines are characterized by repeated, interleaved calibration observations, presently deemed necessary by the Project in order to attain the highest astrometric accuracy. However, the PI and his collaborators have shown (Böker et al. 2000) that the phase calibration accuracy can be as much as a factor 10 lower for imaging than for astrometry, and the images produced from such data may still attain an acceptable dynamic range. An important task for the Imaging and Nulling Mission Scientist will be to work with the Project to define an optimal observing time line for imaging which will increase the observing efficiency, a reasonable goal here being 50%. The scientific return of the mission could be significantly improved if this is operationally possible.

4.1.3 Image formation and restoration

The question of what are the optimum methods (if any) for the restoration of SIM synthesis images has not yet been addressed. The issues here are the (u,v) coverage, the presence of a zero spacing[4], and the presence of photon noise from the signal itself rather than from the instrument.

The general features of the noise in optical synthesis images have been discussed e.g. by Prasad and Kulkarni (1989) and Kulkarni et al. (1991). Kulkarni (1989) has discussed a generalization to radio and infrared wavelengths. The IMSIM code currently includes photon noise in our model of the quadrature detection system used to measure the fringe amplitude and phase on SIM. As mentioned in the previous section, we have also included in later versions of IMSIM the capability to model phase noise as may be caused e.g. by mechanical jitter in the SIM delay line.

A major area where little has been done up to now is the study of restoration methods for improving the quality of images made with SIM. We have included two standard techniques for image restoration in IMSIM, CLEAN and Maximum Entropy, both well-known from radio astronomy (e.g. Perley et al 1994), but we have not carried out any systematic study

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[4] SIM is unique and different from all modern radio synthesis telescopes in this respect.

of which method may be better for the typical image fields to be encountered with SIM, nor have we looked any further at other methods. The PI is well familiar with restoration methods and has co-edited a conference volume on the subject (White & Allen 1991). This will be a focus of attention in the coming years for the SIM Imaging and Nulling Mission Scientist.

4.1.4 Proper motions in crowded fields

An important task of the Imaging and Nulling Mission Scientist will be to act as a resource for members of the Science Team who are also wishing to carry out precision astrometry on targets in crowded fields. Although the PI and his collaborators have begun modeling these effects (Rajagopal et al. 1999), much more remains to be done here. A particularly vexing problem is the repeatability with which the SIM focal plane entrance aperture can be placed on the nominal target position in the sky.

4.2 Demonstration of starlight nulling

The Imaging and Nulling Mission Scientist is charged with ensuring that SIM also meets the third Key Technology Requirement, “Demonstration of Starlight Nulling”. In its simplest form, this will mean assisting the Project with choosing a suitable target star (small enough in angular size to be effectively a point source, bright enough, free of spots, etc.) and designing a specific observation to test the requirement of nulling at a level of 10^4 over time periods of up to 1 hour in a spectral bandwidth of $\geq 20\%$.

A nulling capability has been modeled in imSIM, although the implementation is presently somewhat simplistic and there is room for improvement. In particular we shall incorporate finite-sized star models with the features described above. A program of observations will be constructed which will demonstrate starlight nulling with SIM and determine whether the required level of rejection has been achieved.

Parenthetically we want to point out that, if nulling can be provided on any SIM baseline, and if a full range of baselines is retained in the final SIM design, then we shall be able to carry out some truly unique and remarkable observations. For example, SIM will be capable of measuring the surface brightness distributions of exozodi disks around bright stars at optical wavelengths (Böker & Allen 1999), even revealing inner gaps and rings which may be the signatures of planets. This capability is especially relevant for the future use of the Terrestrial Planet Finder, and as SIM Imaging and Nulling Mission Scientist the PI intends to keep attention focussed on this issue.

4.3 Feeding the SIM experience forward

The Imaging and Nulling Mission Scientist is also tasked with developing **“...a strategy to optimize the technology return from SIM’s imaging and nulling demonstrations for input to future interferometry missions.”** (AO, page 7). The science research and technical programs outlined in this proposal will give the PI the relevant knowledge and experience; what remains to be achieved is to develop effective ways of inserting this knowledge and experience in the places it is needed. Over the past 5 years the PI has succeeded in becoming an effective and authoritative voice for imaging with SIM by feeding 25 years of experience with interferometry and synthesis imaging at radio wavelengths into the SIM Project through formal and informal channels. For the immediate future, perhaps the most relevant follow-on mission to SIM will be TPF, the Terrestrial Planet Finder. The PI is a member (and Deputy for Astrophysics) of the Ball Aerospace Pre-Definition Phase Study Team recently funded by JPL to carry out studies of architectures for TPF over the next $\approx$ 18 months. Feeding the SIM experience forward into TPF will be a natural consequence of the his involvement in both projects.

4.4 Specific qualifications of the PI

The Principle Investigator for this proposal has hands-on experience in interferometry and synthesis imaging, beginning with his second Postdoctoral position in 1969 at the Kapteyn Astronomical Institute in Groningen, The Netherlands, where he had the good fortune to work for more than 15 years with one of the premier synthesis imaging radio telescopes in the world, the Westerbork Synthesis Radio Telescope (WSRT). During this period, his activities included:

- helping to develop one of the first interactive computer data-processing systems for synthesis images (Ekers et al. 1973) which became the basis for a sophisticated image processing system (GIPSY, Shostak & Allen 1980; Allen & Terlouw 1981; Allen et al. 1985) that is still in use today;
- designing the first spectrometer for the WSRT array (Allen et al. 1974) which permitted high-spatial-resolution observations that confirmed the existence of spiral structure in the interstellar gas of nearby galaxies (Allen et al. 1973) and provided the first detailed kinematic data for comparison with theoretical models of spiral structure;
- designing and building a two-element radio interferometer for use as a student demonstration instrument at Groningen University;
- developing management techniques for organizing the software development process in a research group environment (Allen & Ekers 1981);
- developing methods of adding the short-spacing information back into radio synthesis images (Allen & Goss 1979); and
- carrying out extensive science investigations making use of the unique features of the WSRT, and providing leadership to a research group for more than a decade (Allen & Ekers 1980).

In 1985 the PI moved to the University of Illinois as Head of the Astronomy Department, and became involved in the Berkeley-Illinois-Maryland Array project. This project provided him with experience in millimeter radio interferometry, and led to the initiation of several research projects which are still being carried on today, now mostly with the Owens Valley Millimeter Array.

In 1989 the PI moved to the Space Telescope Science Institute as Head of the Science Computing and Research Support Division. In this environment he was responsible for directing the migration of the Institute science computing facilities from a centralized main frame to distributed system of workstations, and for directing the development of the computing systems to be used for the archiving of data from the Hubble Space Telescope.

The PI was invited to join the NASA Space Interferometer Science Working Group in 1993 in order to provide expertise on interferometry and synthesis imaging. This group was tasked by NASA to develop concepts and a strawman science program for the Astrometric Interferometer Mission which had been outlined in the Bahcall Report. He was a co-author and also co-editor of the final report of this working group (SISWG) which was issued in the spring of 1996. At that time (March 1996) he was invited to membership on a special NASA-HQ review panel tasked with advising NASA on the specific choice of spacecraft architecture for the Space Interferometry Mission (SIM). With the choice of the JPL Orbiting Stellar Interferometer as the architecture for SIM, a new Space Interferometry Mission Science Working Group (SIMSWG) was formed in the fall of 1996. The PI joined this group as well, and for the next 3 1/2 years assisted the group with the development of the Science Requirements Document for SIM, authoring the entire Chapter 6 on "Synthesis Imaging and Nulling-Imaging Requirements".

In order to model quantitatively the imaging and nulling-imaging performance of SIM, the PI contracted with JPL to create a computer simulator which was used to construct a strawman imaging and nulling-imaging science program. This project showed, among other things, that SIM was capable of imaging the cores of Active Galaxies in emission lines and of characterizing exo-zodi dust disks around nearby stars (Böker & Allen 1999). Along the way, he developed a tutorial on the Fourier Optics of SIM which he presented as a lecture to the SIMSWG and to JPL SIM Project employees[5].

Most recently, the PI and his collaborators have been modeling the confusion effects on SIM astrometry in crowded fields (Rajagopal et al. 1999) and the effects of instrumental phase instability on the dynamic range of SIM synthesis images (Böker et al. 2000).

In other activities relevant to this proposal, the PI has assisted both the National Science Foundation and NASA-HQ with reviews of ground-based interferometry, and is a member (and Deputy for Astrophysics) of the Ball Aerospace Pre-Definition Phase Study Team recently funded by JPL to carry out studies of architectures for TPF over the next ≈ 18 months. Finally, he has been involved for several years as a science CoI on proposals for ALFA, the "Astronomical Low-Frequency Array" (Jones et al. 1999), a space-VLBI array for mapping solar, Galactic, and extragalactic radio sources at very low frequencies.

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[5] This tutorial is included as an Appendix in the paper by Böker & Allen (1999)

4.5 Involvement of the CoIs

SIM provides a unique opportunity to test the techniques of synthesis imaging at optical wavelengths, and to measure stellar motions in very crowded environments such as are to be found in the neighborhood of a massive black hole. The successful pursuit of this project will require a broad range of knowledge and expertise including a deep understanding of the synthesis imaging process, familiarity with the software and methodology of the data analysis, and knowledge of the latest observational research results on black holes and the behaviour of stars near them. The necessary depth in each of these three areas is not to be found in one individual. We have therefore formed a team which includes individuals possessing this wide range of expertise at great depth. In order to facilitate team interaction, our team members are all co-located at the Space Telescope Science Institute (STScI). STScI currently operates the science program of the Hubble Space Telescope (HST), and has been designated as the Science Operations Center for the Next Generation Space Telescope. STScI also supports the research efforts of more than 70 astronomers in a wide range of subjects.

CoI van der Marel is an expert in the area of observations and models of the structure and dynamics of galaxies and stellar systems, and their nuclei in particular. In recent years he has been the PI on eight different projects of high-resolution imaging and spectroscopy on the HST. In the present project he will focus mostly on the dynamical modeling and interpretation of the SIM data that we propose to obtain. Over the past decade much of van der Marel's work has addressed the construction of axisymmetric stellar dynamical equilibrium models for observed stellar line-of-sight motions in galaxies. These models were used to study the properties of the dark components (central black holes and/or dark halos) in the Milky Way galaxy, elliptical galaxies, globular clusters and clusters of galaxies. The current state of the art are fully non-parametric numerical Schwarzschild models with arbitrary three-integral distribution functions (van der Marel et al. 1998). To properly interpret the SIM data van der Marel will extend these models to include data-model comparison algorithms for systems with discrete data sets (instead of continuous velocity distributions from integrated galaxy spectra) and to include the calculation of model predictions and interpretations of proper motions. He will also initiate ground-based and HST spectroscopic studies to obtain line-of-sight velocity information for the globular cluster targets that we will observe with SIM, in support of the SIM proper motion measurements.

CoI Böker has designed and developed IMSIM, the software package on which the simulations discussed in this proposal are based. During the course of this project, he will work closely with the post-doc on the maintenance, improvement and expansion of the IMSIM code. Of particular interest in this regard is the implementation of more realistic models for instrumental calibration errors, jitter, and detector properties. Using his technical experience and background in astronomical instrumentation, Böker will act as a link between the SIM project at JPL and the post-doc at STScI. He will ensure that the relevant instrument parameters are implemented into the simulator software. Together with PI Allen, he will identify and feed back to the SIM project the impact of critical design decisions on SIM imaging capabilities. Finally, he will assist in the planning, execution, and data reduction of the proposed SIM observations, as well as any necessary preparatory ground-based observations.

5.3 References

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5.4 Statement of Work

5.4.1 Science data products, data volume and delivery plan

The science data products which will result from this program will include the imSIM software, the final crowded-field target list, and the positions and proper motions of dozens of stars in each target field. The distribution of the stars in each target field can be made available as images and tables of positions shortly after the requested data has been gathered at all required (u,v) points. Such intermediate results will be made available in accordance with NASA policy on SIM data release, typically 1 year from the acquisition date of the last relevant measurement. Since the measurement of proper motions will require observations over the full 5-year mission, these final results will only be available after that time. The Principal Investigator will be responsible for the schedule and delivery of the data products to the Science Team.

The data volume involved in this program is not at all high by modern standards; an obervation of a target field will typically produce a final data structure which will be a data cube of size $128 \times 128 \times 80$ 32-bit numbers, or 5.2 MByte. We propose to observe 6 such fields annually, so the final reduced data rate from our project will be only about 30 MBytes/year, for a total of 150 MBytes over the 5-year mission lifetime.

This program will also produce improved versions of the imSIM software simulator and its accompanying user documentation. We presently envisage a new release approximately once per year, depending on the needs of the Science Team. This software will be used to evaluate options for SIM hardware design, and we will report regularly to the Science Team on these points. We expect that imSIM will also be eventually used to process the science data generated by this proposal, and to assist other team members with their crowded-field astrometry programs as needed. Later, if SIM appears capable of providing a complete range of baselines, imSIM can be used to support the development of a full-fledged program of imaging and nulling-imaging with SIM.