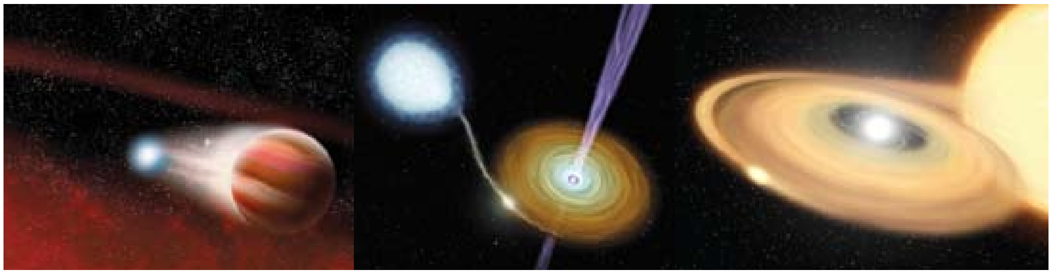
# 9 Black Holes and Neutron Stars



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ABSTRACT

*Black holes and neutron stars are fascinating objects with great potential for testing physical theories in extreme conditions. The gravitational fields near these objects provide an opportunity for tests of General Relativity in the strong-field limit and the properties of matter at the remarkably high densities that exist within neutron stars are unknown. While many of these objects are in binary systems where accreting matter from the stellar companion provides a probe of the compact object, a main difficulty in making measurements that lead to definitive tests has been uncertainty about basic information such as distances to the sources, orientation of their binary orbits, and masses of the compact objects. Through astrometry, SIM Lite will, for the first time, be able to obtain precise distances and proper motions for dozens of these systems and will also be capable of mapping out orbital motion, leading to direct compact object mass measurements. Obtaining such information is critical for a wide variety of investigations that range from probing the space-time around the compact object to constraining the origin and evolution of the systems themselves.*

## 9.1 Matter Under Extreme Conditions

The capability of SIM Lite for precise stellar astrometry will move the field of compact object astrophysics forward by providing measurements of quantities such as black hole and neutron star masses as well as distances to the systems that harbor compact objects. We expect that some of the most exciting results in this area will come from SIM Lite observations of X-ray binaries, which consist of a black hole or neutron star accreting matter from a stellar companion. Hundreds of these systems have been found in our Galaxy by X-ray satellites since the first one was discovered in the early 1960s (Giacconi et al. 1962), and a significant fraction of them are bright enough in the optical for SIM Lite to provide new constraints on these remarkable systems.

When we observe Galactic compact objects, we are probing the most extreme physical conditions in the Universe, providing the most rigorous tests of physical models as well as the opportunity to find new physical phenomena. For example, in discussing possible tests of General Relativity (GR) in the regime of strong gravity, it is often stated that the strongest gravitational potentials are found around black holes, and this is true whether one is talking about stellar mass or supermassive black holes. However, Psaltis (2008) points out that the relevant parameter for determining the “strength” of a gravitational field is the space-time curvature, and this quantity is a trillion times larger in the vicinity of a 10 $M_\odot$ black hole than it is for a $10^7$ $M_\odot$ supermassive black hole. Thus, it is near the smaller compact objects (both black holes and neutron stars) where any deviations from GR due to strong gravity will be largest.

In addition to the great interest that these objects hold for gravitational studies, determining the properties of neutron star interiors is important for nuclear and particle physics. Although current measurement techniques still do not strongly constrain these properties, it is thought that the densities in neutron star cores may be as much as an order of magnitude above nuclear densities (Lattimer and Prakash 2007), making this the location of the densest material in the Universe and making it critical to determine what form matter takes at these densities. Extreme aspects of X-ray binaries include the interaction of accreting matter with very high neutron star magnetic fields (Coburn et al. 2002) as well as the relativistic jets that are very commonly seen streaming away from neutron stars and black holes (Fender 2006), though the details of their production are yet to be fully understood.

Through precision measurements of these systems, SIM Lite has the potential to address many of the questions that are currently the most difficult to answer. Determinations of the source luminosities, mass accretion rates, radii of neutron stars, sizes of accretion disks, and jet size-scales and velocities all depend on knowing the distances to these systems. While reliable distances to most X-ray binaries have been very difficult to obtain, SIM Lite will provide parallax distance measurements for any system in the Galaxy that is sufficiently bright in the optical. Through orbital measurements, SIM Lite can directly address the question of the properties of matter inside neutron stars by measuring their masses, and both neutron star and black hole studies will benefit from SIM Lite’s determination of binary inclinations, which is typically the largest contributor to the error on the compact object’s mass.

While distances and masses will be a major step forward, SIM Lite will also measure the proper motions of these systems, which will help to determine their birthplaces as well as answer the question of whether a supernova is required for the formation of a black hole. For systems with radio jets or other sources of radio emission, SIM Lite will provide an absolute reference frame that will constrain where in the system the radio emission originates. For this application and also for the study of other variable phenomena in these systems, it is notable that the flexible scheduling (e.g., the possibility of “target of opportunity” observations) that SIM Lite allows is critical. In the following material, we discuss in more detail several of the investigations that SIM Lite will enable.

## 9.2 Overview of SIM Lite Targets

Most of the currently planned SIM Lite targets we discuss in this chapter are X-ray binaries. These types of systems are usually divided into low-mass X-ray binaries (LMXBs), which have K- or M-type companions and masses below 1 $M_\odot$, and high-mass X-ray binaries (HMXBs), which have massive O- or B-type companions. Systems that do not fall into these categories (e.g., those with A- or F-type companions) are often called intermediate-mass X-ray binaries (IMXBs), and LMXBs may descend from IMXBs through a phase of thermal mass transfer (Tauris and van den Heuvel 2006). Selecting the best targets for SIM Lite to observe depends on several considerations, including the optical brightness of the targets, their distances, the sizes of their binary orbits, and the level of scientific interest.

Generally, the HMXBs are the best for orbital measurements due to their optical brightness and large orbits. HMXB orbital periods are typically several days to months compared to hours to a couple of days for LMXBs. In Unwin et al. (2008), we list 16 neutron star HMXBs with orbital astrometric signatures (i.e., the angular size of the semi-major axis of the optical companion's orbit) between 4 μas and 1 mas. Half of these have signatures >40 μas. Such signatures are large enough to allow for a precise determination of the binary orbit with SIM Lite (see Figure 9-1). In addition to the neutron star sources, there are black hole HMXBs, such as Cygnus X-1 (see Section 9.6), SS433, and V4641 Sgr, for which we expect SIM Lite to determine their orbits.

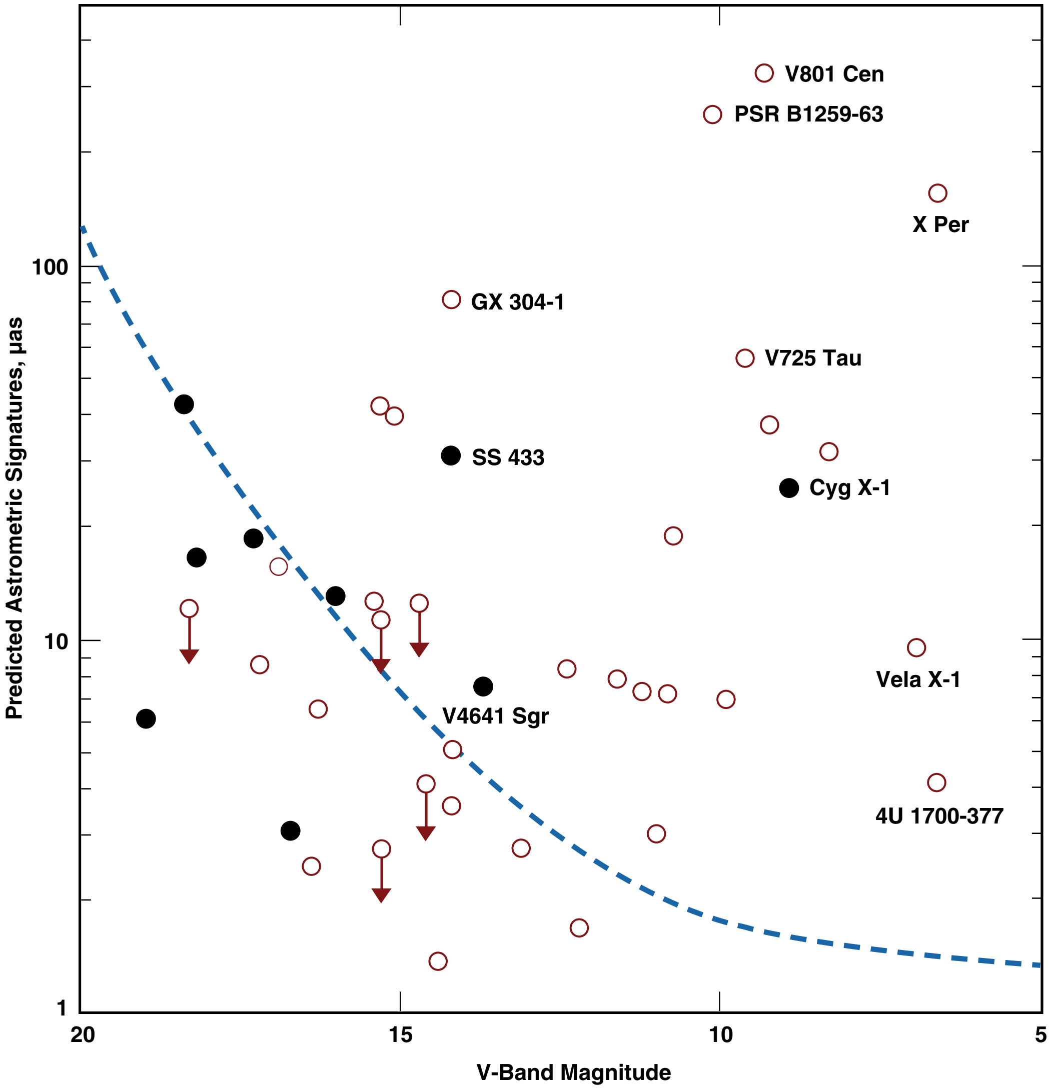

Figure 9-1. Expected astrometric signature from orbital motion vs. V-band magnitude for neutron star (white circles) and black hole (black circles) X-ray binaries. The dashed blue line shows the threshold for detection of orbital motion in 40 hours of SIM Lite mission time. The threshold is defined as the level at which the system's semi-major axis is 10 times larger than the astrometric noise per observation (i.e., the single-measurement accuracy) divided by the square root of the number of observations.

Distance and proper motion determinations with SIM Lite are feasible for any Galactic system that is optically bright enough, and targets will include all types of X-ray binaries. However, it is probably the LMXBs that will benefit most from improved distance measurements since the current estimates of their distances can be uncertain by a factor of two or more. SIM Lite will be capable of distance and proper motion measurements for at least the 27 LMXBs with V-band magnitudes brighter than 20 (Unwin et al. 2008), providing distances to 1 to 6 percent accuracy in most cases. Some of these LMXBs are radio jet sources, and there are also plans to observe RS CVn and Algol-type binaries with radio emission.

Gaia will only be able to do a small subset of the black hole and neutron star science described here. While Gaia may obtain orbital measurements for a few of the brightest HMXB systems with the largest astrometric signatures, the μas measurement capabilities of SIM Lite are absolutely essential for the vast majority of our planned targets, including the interesting neutron star source Vela X-1 (see Section 9.3). The situation is similar for LMXB distances in that obtaining accurate distances for the brightest and closest LMXBs is expected to be feasible for Gaia. However, of our 27 LMXB targets, 19 have magnitudes fainter than V = 17 and most of these are estimated to have distances of 5 to 10 kpc. Of these 19 fainter LMXBs, there are only five for which Gaia is expected to obtain distance measurements to better than 40 percent accuracy (Lindegren et al. 2008). For these five LMXBs, Gaia will obtain distances to 15 to 33 percent while the SIM Lite distances are expected to be 10 times more accurate (1.6 to 3.3 percent). Finally, as mentioned above, the planned observations make use of the SIM Lite capability to perform target of opportunity observations, which will not be possible with Gaia.

## 9.3 Inside Neutron Stars

Although the inside of a neutron star is certainly hidden from direct viewing, significant constraints on the composition can be obtained by measuring masses and radii of neutron stars. This is because the pressure-density relationship (i.e., equation of state, EOS) that is theoretically calculated for various neutron star compositions directly predicts the star's mass-radius relation. Lattimer and Prakash (2001) discuss the different types of matter that may be inside neutron stars, including normal matter (neutrons and protons) as well as exotic matter such as hyperons, kaon condensates, and quark matter. Constraining the composition of neutron star interiors has important implications for fundamental physics, including understanding the nature of strong force interactions at high densities and determining if strange-quark matter is the ultimate ground state of matter.

Observations of neutron star HMXBs with SIM Lite have the potential to place significant constraints on the EOS. Each EOS predicts a maximum neutron star mass, so an accurate mass measurement for even a single neutron star above the maximum value predicted by an EOS would rule out that EOS. Although Thorsett and Chakrabarty (1999) found that many neutron stars have masses that are close to the canonical value of 1.4 solar masses, which allows essentially all EOSs, more recent observations have shown evidence for more massive neutron stars with median mass measurements in the 1.8 to 2.8 $M_\odot$ range (Barziv et al. 2001; Clark et al. 2002; Freire et al. 2008). Confirming these high neutron star masses by reducing the uncertainties would lead immediately to ruling out a large fraction of the proposed EOSs.

As mentioned above, SIM Lite will be able to detect orbital motion for at least 16 neutron star HMXBs and the best mass constraints will be obtained for the accreting X-ray pulsars. For five SIM Lite HMXB targets, the neutron star orbit has already been very accurately mapped (Bildsten et al. 1997; Unwin et al. 2008), and when this is combined with a SIM Lite measurement of the companion's orbit, a direct neutron star mass measurement will be obtained. One of the most tantalizing of these targets is Vela X-1, which has a current neutron star mass measurement of 1.86 ± 0.16 $M_\odot$ (68 percent confidence errors, Barziv et al. 2001). Simulations have shown that when SIM Lite measurements are combined with the X-ray measurements, it will be possible to measure the neutron star mass to 3.9 percent accuracy (Tomsick et al. 2005; Unwin et al. 2008). This is a major improvement over the current mass measurement and will be sufficient to determine if Vela X-1 harbors an over-massive neutron star. As our estimate of the astrometric signature for Vela X-1 is 9.5 µas, the SIM Lite capabilities are critical.

SIM Lite will also contribute to constraining the neutron star EOS by improving constraints on the neutron star radius by accurately determining the distance to neutron star X-ray binaries. There are at least two radius determination techniques that use X-ray measurements for which uncertain distances are a primary source of radius uncertainty. First, when X-ray transient systems are at their lowest flux levels, the X-ray emission is dominated by blackbody emission from the neutron star surface (Rutledge et al. 2002, Lattimer and Prakash 2007). Knowing the distances to sources like Cen X-4 and Aql X-1 will remove a major uncertainty in the radius measurement. Thermal X-ray emission is also seen from the entire surface of the neutron star when actively accreting neutron star systems undergo X-ray bursts. While this is a promising technique for measuring neutron star radii, source distances are the primary uncertainty (Galloway et al. 2008).

## 9.4 Probing Strong Gravity

Both distance and orbital measurements of X-ray binaries by SIM Lite are important for probing the strong gravitational fields near black holes and neutron stars, potentially allowing for tests of GR. One GR prediction that SIM Lite can contribute to testing is that black holes should, by definition, have an event horizon, i.e., a geometrical boundary from which not even light can escape. Observational evidence for this comes from a comparison of the X-ray luminosities of black hole and neutron star transients when they are at their lowest flux levels, presumably with a very low level of mass accretion. The most up-to-date results show good evidence that the black hole systems are, in fact, less luminous than neutron star systems (Narayan and McClintock 2008), and a very likely interpretation to this difference is that the accreted mass is advected through the black hole event horizon (Narayan et al. 1997). Still, it is notable that although this result rests on luminosity measurements, not one of the systems used to obtain the result has a direct distance measurement. Several of the systems are bright enough to have their distances measured with SIM Lite, which would be a major improvement to the study.

A second GR prediction that is being tested is that black holes and neutron stars should have an innermost stable circular orbit (ISCO). The implication of an ISCO is that since there are no stable orbits within some radial distance from the compact object, the accretion disk should be truncated at that radius. There are at least two techniques that are being applied to X-ray observations of actively accreting black holes with the goal of finding the location of the ISCO. One of these relies on measuring the shape of the iron K$\alpha$ emission line, which is produced when X-rays incident on the accretion disk cause the iron in the disk to fluoresce. At the inner edge of the accretion disk, the motion of the accretion disk material produces red and blue Doppler shifts and the gravitational field produces a redshift, causing the emission line to be extremely distorted (Tanaka et al. 2005; Miller 2007). The measurement of the inner radius comes from modeling the shape of the line, but in addition to the location of the inner radius, the shape of the line also depends on the inclination of the accretion disk. Thus, one major contribution that SIM Lite can make to this study is to measure the binary inclination, which should be the same as the disk inclination. Two black hole systems with iron line measurements for which SIM Lite will be able to constrain the binary inclination are Cyg X-1 and GRO J1655-40. In the case of Cyg X-1, the best estimate for the orbital astrometric signature is in the range of 27 to 34 µas (also see Section 9.6), making it an easy target for orbital studies that will measure the binary inclination precisely (Pan and Shaklan 2005; Unwin et al. 2008).

Another ISCO measurement technique that would greatly benefit from precision measurements with SIM Lite is the effort to use the thermal continuum emission from black hole accretion disks to determine the location of the inner edge of the disk. There are times when this component dominates the X-ray emission from black hole systems, and its shape is well described by thermal spectral models. Using fully relativistic models, McClintock et al. (2006) have carried out detailed analyses for several sources to find the location of the inner radius of the disk. While the work has been successful, both distance and accretion disk inclination are uncertain parameters in the interpretation of the results (Psaltis 2008) and these are parameters that are accessible to SIM Lite.

## 9.5 Birth and Evolution of Black Holes and Neutron Stars

In order to place black holes and neutron stars in the larger context of stellar life cycles, including questions related to stellar and binary evolution as well as connections to phenomena such as supernovae (or “hypernovae”) and gamma-ray bursts, it is of great importance to investigate how and where these compact objects are born. By measuring the proper motions and distances to X-ray binaries, SIM Lite can help to answer this question for a large number of sources. When combined with systemic radial velocities that can be obtained using spectroscopy, proper motions and distances provide a three-dimensional space velocity that can be used to determine the object’s runaway kinematics (e.g., “kick” velocity) as well as its Galactocentric orbit (Mirabel et al. 2001; Mirabel and Rodrigues 2003a). In many cases, this information can be used to test relationships between specific sources and nearby clusters of stars (e.g., Cyg X-1 and its nearby OB association) or to constrain whether a source was born in the plane of the Galaxy or out of the plane in a globular cluster.

To date, the radio and Hubble Space Telescope (HST) proper motion measurements that have been made for a few black hole systems have provided very interesting results. While results for two black hole LMXBs (GRO J1655-40 and XTE J1118+480) show space velocities consistent with the systems having received a supernova kick at the time of the birth of the black hole (Mirabel et al. 2001; Mirabel et al. 2002), the very low space velocity for Cyg X-1 indicates that less than 1 solar mass of material could have been ejected when the black hole was formed, suggesting that the Cyg X-1 black hole came from the collapse of a massive star without a supernova (Mirabel and Rodrigues 2003b). Unfortunately, the current measurement precision for proper motions is only sufficient for the most nearby systems. SIM Lite will provide at least two orders of magnitude improvement for proper motion measurements over HST, which will greatly increase the number of systems for which accurate proper motion measurements are possible.

## 9.6 Black Hole Masses and the Case of Cyg X-1

Mass is one of the fundamental properties of a black hole, and it has important implications for the strong gravity studies discussed in Section 9.4 as well for understanding the birth of black holes and the evolution of the X-ray binaries in which they are found (Section 9.5). Theoretical predictions for the mass distribution of black holes that result from the deaths of massive stars rely on a wide range of physics, including the maximum mass of a neutron star (see Section 9.3), the strength of the stellar winds of the progenitor stars, and the details of supernova explosions as well as the necessary conditions for supernovae to occur. From theory and simulations, Fryer and Kalogera (2001) predict a continuous distribution of black hole masses with the largest number of black holes being just above the maximum neutron star mass (between 1.5 and 3 $M_\odot$) and a gradual drop in the numbers of black holes with higher masses.

Currently, black hole mass estimates have been obtained for 20 black hole systems, and when the relatively large uncertainties in the estimates are taken into account, the possible masses range from 3 to 18 $M_\odot$ (Remillard and McClintock 2006). While comparisons between these measurements and the theoretical predictions are still difficult due to the relatively small numbers of black holes and the large uncertainties in the mass estimates, the range of measured masses is very similar to the predictions. To go beyond such rough comparisons requires the largest number of black hole masses to be measured as accurately as possible. Both uncertain binary inclinations and distances make large contributions to the current errors in the mass measurements and SIM Lite can make an important contribution to this study by measuring these parameters to provide accurate mass determinations.

The first discovered stellar black hole, Cyg X-1, is a good example of the need for SIM Lite's capabilities. The estimates of mass and distance for Cyg X-1 are still controversial even though the source has been suspected of harboring a black hole since the early 1970s. One controversy has been the mass of the O9.7 Iab stellar companion. Although an isolated star with this spectral type would have a mass near 33 $M_\odot$, in a binary, mass transfer and binary evolution can cause the mass to be considerably less. Herrero et al. (1995) give a best estimate for the companion mass of 17.8 $M_\odot$, which would indicate a black hole mass of 10.1 $M_\odot$ using the best estimate for the binary inclination of 35 degrees. A plausible lower limit on the companion mass of 10 $M_\odot$, combined with an upper limit to the binary inclination of 65 degrees (based on the absence of X-ray eclipses), leads to a black hole mass of 4 $M_\odot$. For possible ranges of the black hole and companion masses, we present the astrometric signatures in Table 9-1. We have assumed the largest likely distance for Cyg X-1 of 2.5 kpc, but it should be noted that parallax measurements put the distance at 1.7±1.0 kpc (Hipparcos) or 1.4±0.9 kpc (VLBI), which would make the astrometric signatures even larger. Even at the larger distance, the wobbles of Cyg X-1 are in the range of 20 to 30 µas for the most likely combinations of component masses, providing an excellent opportunity for SIM Lite to provide a long-awaited definitive measurement of the compact object mass in this system.

Table 9-1. Astrometric signatures (in µas) due to binary motion in Cyg X-1 for different combinations of companion star and black hole masses (a distance of 2.5 kpc is assumed). The full range is measurable by SIM Lite.

| Companion Mass, $M_\odot$ | Black Hole Mass, $M_\odot$ | | | | |
|---|---|---|---|---|---|
| | 17.5 | 15 | 10 | 7 | 3.5 |
| **10** | — | — | 33.5 | 26.1 | 15.2 |
| **20** | 38.6 | 34.6 | 25.6 | 19.2 | 10.5 |
| **30** | 32.9 | 29.3 | 21.1 | 15.6 | 8.3 |
| **40** | 29.0 | 25.6 | 18.2 | 13.3 | 7.0 |
| **50** | 26.1 | 22.9 | 16.1 | 11.7 | 6.1 |

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