# 12 Astrometric Reference Frame Science

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ABSTRACT

*The establishment of an inertial reference frame based on grid stars anchored with extragalactic sources will allow for the first time the direct detection of the motion of the Solar System within the Milky Way as well as the Local Group toward the Virgo cluster at the μas/year level. All of this will be accomplished by observing stellar motions with respect to distant "fixed" quasars, which provide an inertial frame against which absolute proper motions can be measured. At the same time, this inertial frame enables possible detection of the apparent motion of the center of light of some "peculiar" quasar sources. By establishing an accurate link between the optical SIM Lite frame and the radio International Celestial Reference Frame (ICRF), high-resolution imaging data at these different wavelengths can be accurately lined up for absolute positional correlation. This enables a better understanding of the mechanisms giving rise to their spectral energy emission.*

## 12.1 Introduction

SIM Lite is an astrometric mission capable of defining a global grid of stars with positions to 4 μas (Makarov and Milman 2005), along with approximately 50 extragalactic sources to similar precision, will establish a new reference frame that will calibrate all the studies of the SIM Lite mission and be applicable to many other astrophysical studies. Here we discuss the inclusion of quasars into the SIM Lite grid and the resulting improvements in the SIM Lite reference frame. In addition, we discuss the science that can be accomplished on the objects comprising the frame, namely the quasars themselves, and the science enabled by a more precise SIM Lite grid and by an accurate tie to other celestial reference frames.

## 12.2 Quasars and the SIM Lite Astrometric Grid

Aside from their astrophysical properties, which can be studied with SIM Lite (see Chapter 11), quasars are critical objects for the formation of a robust astrometric grid. This grid frame forms the astrometric bedrock on which all other SIM Lite observations are built. Even the narrow-angle differential astrometry (e.g., planet detection and microlensing) relies on the grid solution in determination of baseline and instrument parameters.

SIM Lite grid simulations using grid stars alone have shown that the resulting astrometric grid has two undesirable properties. First, there is a relatively large offset in the parallax common to all grid stars from mission realization to mission realization, known in astrometry as zero-point error. Second, the entire frame formed by the grid can spin about some arbitrary axis at an arbitrary rate and thus be non-inertial. Quasars, in particular radio-quiet quasars (RQQs) with little or no optical jet emission, are ideal additions to the grid that can correct these defects. Quasars are typically so far away (of order 1 Gpc) that on the μas scale they have no parallax and probably no peculiar proper motion. Our extensive analysis and simulations have shown that quasars are ideal objects to remove both the grid frame parallax bias and other large-scale distortions (zonal errors), and the residual spin. For example, the overall accuracy of parallax with only 23 quasars in the grid improves significantly, as seen in Figure 12-1.

Figure 12-1 displays the probability density distribution of the mission-average absolute parallax error for 13,000 individual SIM Lite mission realizations with grid stars only (blue histogram). Although the median and the mode performance are within the goal requirements, the long sloping tail of the distribution toward larger errors shows that accidentally poor performance cannot be precluded. With only 23 quasars in the grid, the probability distribution (red histogram) becomes narrow and the tail is eliminated. Consequently, a dramatic improvement is observed in confidence intervals on the mission performance; for example, the 99 percent confidence on the parallax accuracy improves by more than a factor of 2. Other studies have been performed that show how the gain in astrometric performance and confidence varies as function of the number of quasars used and the length of time that they are observed. Using vector spherical harmonics to fit quasar proper motions resulting from the residual frame spin allows this spin to be removed from all objects. Figure 12-2 illustrates distribution of potential SIM Lite grid quasar targets on an Aitoff equal-area projection of the celestial sphere.

In summary, quasars are a practical insurance policy for the SIM Lite mission to achieve excellent astrometric performance, for a cost of only a few percent of the total mission observing time. Photometric observations (Ojha et al. 2008) of selected, bright ($R \leq 16$; UBVRI system) quasars show that more than 50 suitable candidates are available with a sufficient homogeneous sky distribution. These 50 sources will be observed numerous times each during the mission resulting in single measurement accuracy of 16 μas and mission accuracy of 4 μas.

Figure 12-1. Comparison of the simulated SIM Lite astrometric grid accuracy with and without quasars. Monte Carlo simulations show that without quasars in the grid (blue histogram), the possibility of poor mission performance, while small, cannot be precluded. But when only 23 quasars are included in the grid (red histogram), the probability distribution becomes narrow and the most probable accuracy is greatly improved.

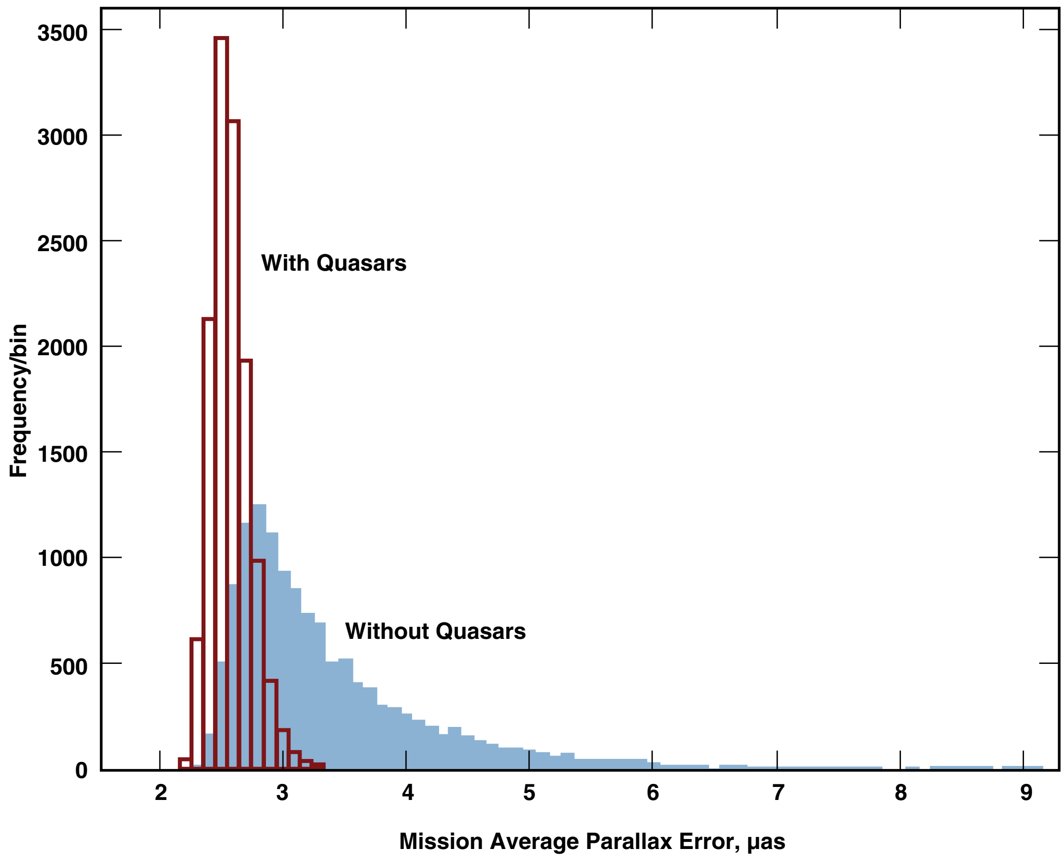
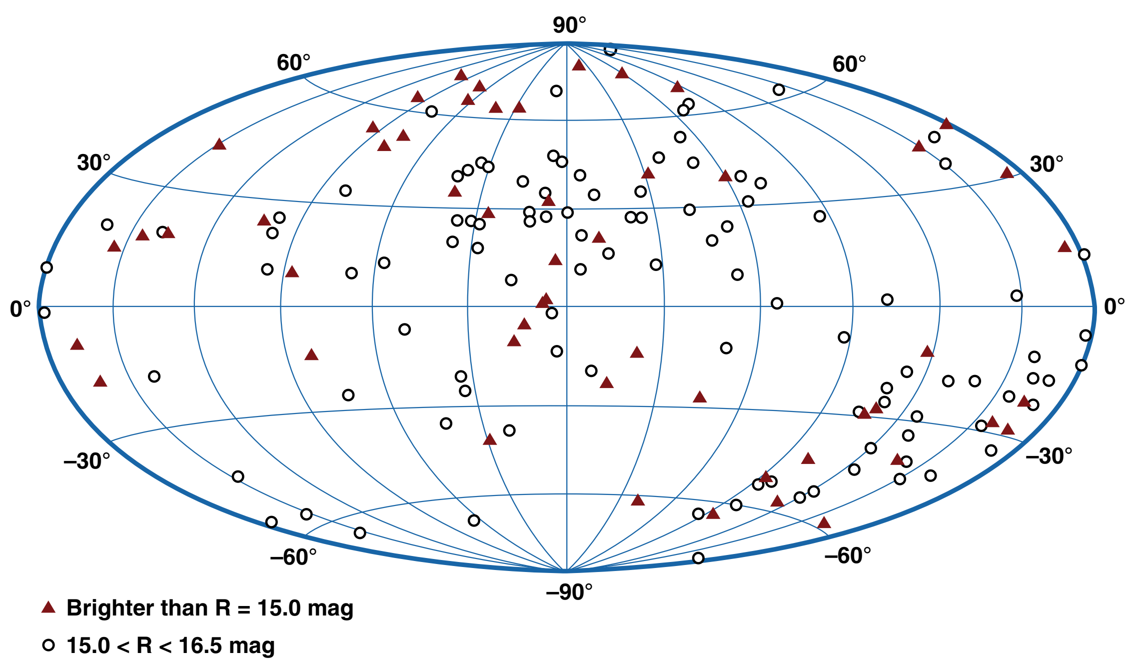



Figure 12-2. Distribution of potential SIM Lite grid quasar targets on an Aitoff equal-area projection of the celestial sphere. USNO photometry for the SIM Lite Project (2005–2007) shows quasars brighter than R = 15.0 mag as red triangles and quasars in the range 15.0 < R < 16.5 mag as open circles.



## 12.3 SIM Lite–Gaia Complementarity

SIM Lite and Gaia are the next-generation astrometry missions and almost perfectly complement one another, as is well illustrated in Table 12-1. Thus, while SIM Lite will observe fewer objects than Gaia, these objects will have better single-measurement errors (SMEs) and end-of-mission life accuracies, and will be observed more times. In particular, Table 12-1 shows that, for a given magnitude, SIM Lite has a factor of 10 better SMEs, an advantage that will be leveraged to the maximum extent in all the astrophysics it will undertake, and in particular in the quasar and grid astrophysics that are described in Chapter 11. This complementarity is primarily due to the fact that SIM Lite is a pointed instrument where variable integration times are used based on object magnitude, whereas Gaia is a scanning instrument with constant integration time independent of magnitude. SIM Lite, like Gaia, uses quasars as fiducial markers to determine the parallax zero point, the frame spin, and the International Celestial Reference Frame (ICRF) frame tie.

Systematic and zonal errors prove to be the most intractable kind of imperfections in the global astrometry because it is often difficult or impossible to find out their origin and predict their character. At the same time, these imperfections become the main concern for astrophysical research involving large sets of objects, for example, determination of the distance to the Large Magellanic Cloud (LMC) or detection of tidal streams and Galactic merger remnants. We do not know enough about the propagation of zonal errors in Gaia to make a detailed comparison, but one fact is evident: these errors will be very different for Gaia and SIM Lite because of the mission architectures and the astrometric methods that have little in common. SIM Lite will have relatively large imperfections at the largest scales on the sky comparable to $4\pi$, whereas Gaia will probably suffer from zonal errors on the intermediate scale (15 to 50 degrees) where SIM Lite achieves the highest accuracy. Therefore, a comparison of the two reference systems will not only reveal these imperfections, but will probably allow us to correct them by combining the results.

Table 12-1. Estimated errors for SIM Lite and Gaia quasar observations.

| Spacecraft | End-of-Mission Accuracy, µas | Single-Measurement Error, µas | V mag | No. of AGN and Quasars Observed | No. of Obs. | Radio-Loud Fraction |
|---|---|---|---|---|---|---|
| **SIM Lite: Science** | 4 | 11 | 13–18 | 50[b] | 150 | 80% |
| **SIM Lite: Grid** | 4 | 16 | 16 | 50[a] | 150 | 40% |
| **Gaia** | 25<br>70<br>200 | 150<br>400<br>1200 | <16<br><18<br><20 | 200[c]<br>20,000[c]<br>500,000[c] | 80–100<br>80–100<br>80–100 | 10%<br>10%<br>10% |

[a] Measurement cadence matches grid star measurement cadence
[b] Measurement cadence determined by science
[c] Measurement cadence determined by mission design

## 12.4 Grid Science

Establishing the SIM Lite frame is a no-cost benefit to the other SIM Lite science projects, as no additional observing time is required besides the routine grid and extragalactic source observations, nor are changes required in the instrument design or observing schedule. For example, the parameterized post-Newtonian (PPN, Will 2006) prediction for small bending of light in gravitational fields [correction factor, $(1 - \gamma)$], can be tested to a few parts in $10^{-5}$. SIM Lite will make a significant contribution in the verification of the principles of General Relativity and in testing the causal nature of the gravitational field by making ultraprecise measurements of star positions close to the major planets of the Solar System, in particular, Jupiter and Saturn. When a planet happens to pass near a background star, the light rays from the latter become deflected by the gravitation of the planet. Utilizing to the full extent the pointing capabilities, the small-field aperture, and the unprecedented precision of small-angle differential observations with SIM Lite, the deflection angles can be measured as functions of time for predicted limb-grazing passages of major planets near brighter stars. Several differential observations with SIM Lite will make it possible to determine not only the main monopole component of this deflection, but also, for the first time, the quadrupole component caused by the oblateness of the planet (Kopeikin and Makarov 2007). Furthermore, the gravitomagnetic term in this deflection, caused by the radial Doppler correction to the planet mass, will amount to a few µas in some instances. Taking several measurements at different relative orbital velocities will enable us to differentiate this exotic effect (not yet observed) from the possible contribution of the scalar gravitational field represented by the $\gamma$ parameter.

The proper motions of extragalactic sources will display secular aberration drift due to the Sun's orbit around the center of the galaxy. The Sun's own motion in the Galaxy shifts the apparent positions of all stars and quasars in a dipole pattern on the sky (Kopeikin and Makarov 2006). The pattern of secular aberration is in fact not static, but will slowly change with time because of the Sun's galactocentric motion and other components of acceleration. SIM Lite astrometry, at its unprecedented level of precision, will be quite sensitive to this gradual change, which manifests itself as a predictable pattern of apparent angular motions (proper motions) of all objects on the sky. Therefore, quasars will also be involved in this gradual motion on the sky with amplitude of approximately 4.2 µas yr$^{-1}$ (Figure 12-3). Global astrometry of 50 stable grid quasars during five years will allow us to detect and directly determine the solar acceleration in the Galaxy.

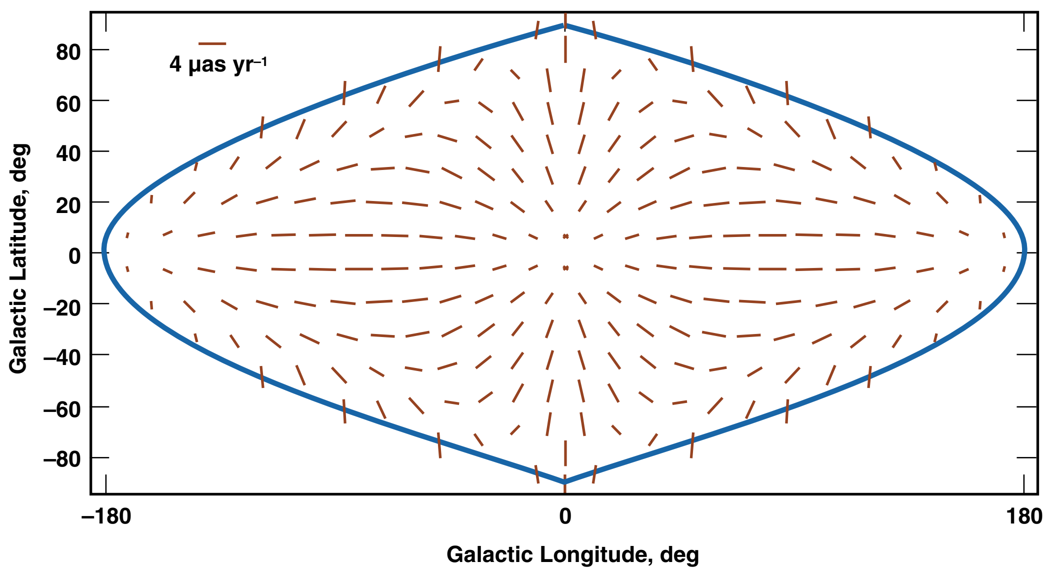



Figure 12-3. Simulated secular aberration effect over the celestial sphere showing the effect of the Sun's galactocentric motion, measurable by SIM Lite. This must be fit to the frame quasars used to calibrate the astrometry. Deviations from this pattern will result from changes in the Sun's galactrocentric motion and from gravitational deflections due to massive bodies in our vicinity, including Jupiter and Saturn. This will also probe whether the Sun has a dim companion, long a subject of speculation.

Astronomers have been discussing the intriguing possibility that the Sun has a dim companion (Nemesis) on an eccentric orbit. SIM Lite will be able to detect any invisible gravitating body in our vicinity in an elegant way if this body is close and massive enough. Any acceleration of the Sun (and SIM Lite) caused by the gravitational pull from the companion will be observable as a systematic pattern of apparent proper motions of distant quasars. The axis of this pattern will indicate the direction in which such a companion should be visible. Calculations show that a body more massive than 0.33 $M_J$ (mass of Jupiter) will be safely detected within 100 AU, and anything more massive than 330 $M_J$ within 3160 AU.

Cosmological models of the early Universe imply the existence of relic gravitational waves (GW), including inflation and anisotropic phases. The present-day energy density of these long-period waves is expected to be of order $\Omega_{GW}h^2 \approx 10^{-9}$ and comprise different modes of polarization and power spectrum. A plane monochromatic, linear-polarized GW propagating through the local part of the Universe bends light rays from distant sources in the transverse directions. The latter effect is observable with SIM Lite as apparent motion of quasars on the sky. Because of the quadrupole nature of GW radiation, ~80 percent of power spectrum is carried by second-order vector harmonics of the proper motion field (Gwinn et al. 1997). Most theorists estimate the energy of relic GW to be too small to be actually detected with SIM Lite. However, detection of GW from anisotropic phases in the early Universe may be possible in coherent spectral lines because of the "broadband" nature of astrometric measurements, in that the apparent motion of an object would integrate the wave power over a certain interval of frequency. A nondetection would put upper limits on the energy carried in such coherent spectral lines, with significant implications for cosmology.

## 12.5 Frame-Tie Science

The current realization of the ICRF is based on very long baseline interferometry (VLBI) positions of sources with accuracies on the order of 300 µas. This accuracy is expected to improve to order 50 to 100 µas with the release of ICRF-2 in the near future. SIM Lite observations of ICRF sources need only to be made to this accuracy to align the SIM Lite frame with the ICRF. There will be an overlap of about 30 sources between the SIM Lite and ICRF frames.

An accurate tie between the SIM Lite frame and the ICRF will provide valuable insights into the physics of quasars and their jets. By directly linking the frames through quasar astrometry, one will be able to investigate the relationship between the radio core and optical photocenter at unprecedented accuracies. Scientific studies related to the linking of the frames will investigate correlations between the variability, separation, motion, and direction of radio/optical jet components close to the point of origin. In addition, an accurate tie between the frames will enable a variety of multi-wavelength scientific studies of both galactic and extragalactic sources. See Chapter 11 by Wehrle et al. for more details on quasar science.

Given the ability of future astrometric satellite missions to directly observe quasars, future ties between the optical and radio frames will naturally be accomplished through observations of such compact extragalactic objects. To enable a high-precision tie between the SIM Lite and ICRF frames, candidate quasars must necessarily exhibit a high degree of astrometric stability at both radio and optical wavelengths. It is well known that the structure of the emission at cm wavelengths has a significant impact on astrometric stability (Fey and Charlot 1997, 2000). This impact is reduced as the observations move toward the mm regime (Charlot et al. 2008). However, the effects of optical source structure and photocenter wander on the µas-level astrometric precision expected for SIM Lite is a completely unexplored region of phase space.

### 12.5.1 Frame-Tie Quasars

Quasar optical emission may originate from three potential sources: thermal emission from the accretion disk surrounding the black hole, nonthermal coronal disk emission, and for a subset of the extreme radio-loud quasars (i.e., blazars), nonthermal emission from knots in the relativistic jet. Recent results by Marscher et al. (2008), involving simultaneous VLBI and optical polarimetric monitoring, suggest that these knots of optical emission move outward through an acceleration and collimation zone toward a standing conical shock region thought to be the "core" at millimeter wavelengths. Studies involving the tie between the SIM Lite and radio reference frames have the potential to greatly improve our understanding of this phenomenon by registering and tracking the wander of the optical photocenter relative to the radio core and by correlating changes in the radio and optical flux. Since SIM Lite is a pointed mission rather than a scanning mission, frame-tie investigations will almost certainly take advantage of multi-epoch concurrent SIM Lite/VLBI observations, thus improving both the frame link and the quasar science (see Figure 12-4).

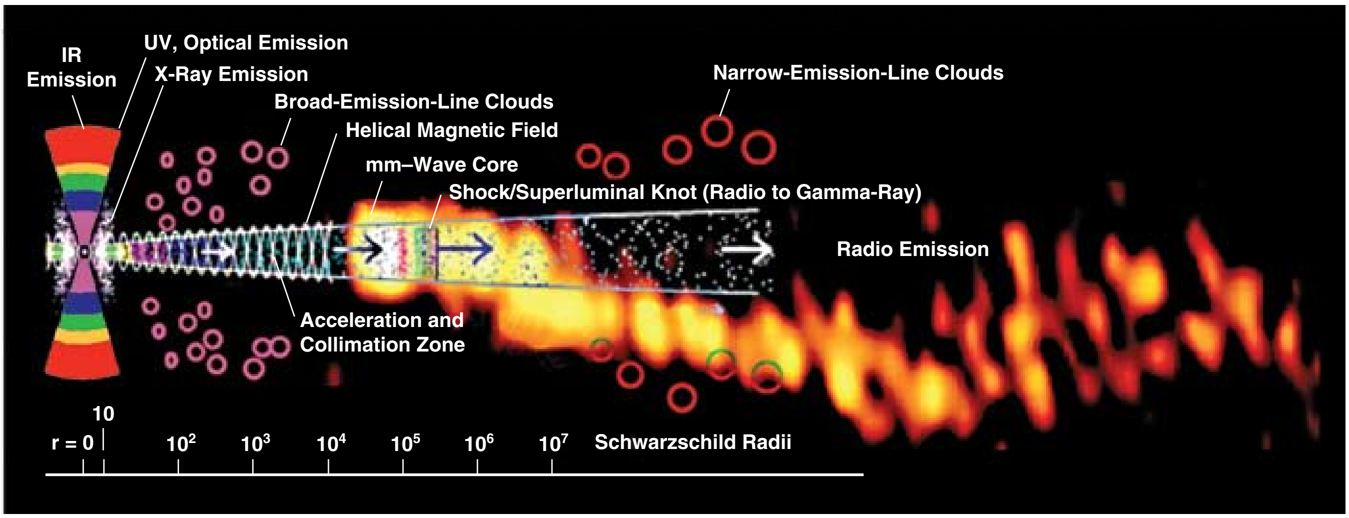


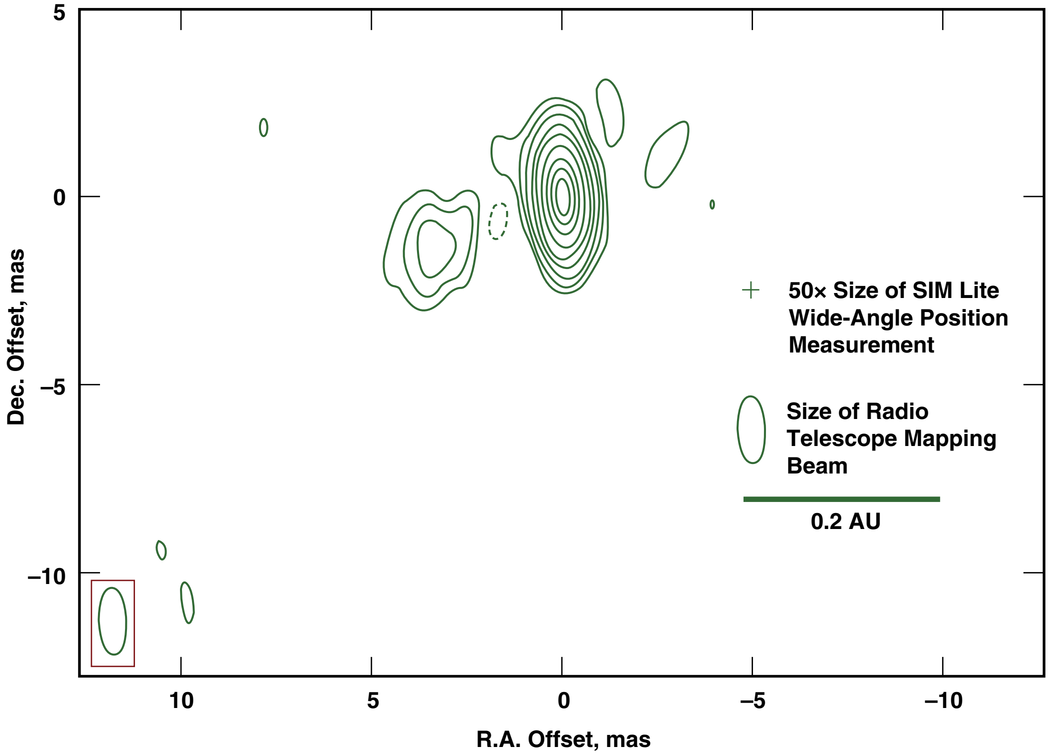

Figure 12-4. Overlay of 3 mm radio image of the blazar 3C454.3 (Krichbaum et al. 1999) on a diagram of a quasar from Marscher et al. (2008), not to scale. The figure shows the potential frame-tie quasar science that could be accomplished with SIM Lite. Knots of optical emission move outward from the black hole's accretion disk (left) through an acceleration zone toward the millimeter and radio "cores" and radio jet (right). Concurrent SIM Lite and VLBI observations will register and track the wander of the optical photocenter relative to the radio core.

### 12.5.2 Multi-Wavelength Science Enabled by the Frame Tie

There are a variety of galactic sources (e.g., microquasars, RS CVn binaries, Algol binaries, late-type stars, X-ray binaries, etc.) for which an accurate frame tie would enable multi-wavelength science. For SIM Lite, observations will be limited to systems with either a large difference in magnitude between the primary and secondary stars or orbital separations of order of the fringe spacing of the interferometer. Figure 12-5 provides an example of an RS CVn binary system, σ Geminorum, for which the radio emission could be tied to the SIM Lite–determined positions of the stars in the binary. The system consists of a K1 III giant primary with $M_V = 4.15$ and a companion that is unseen in both photometric and spectroscopic observations. The radio emission as measured with VLBI shows a double-lobed structure with the lobes separated by ~3.4 mas. Interestingly, the major axis of the spectroscopically determined orbit is $2\ a \sin(i) = 0.13$ AU (~3.4 mas at the assumed distance to σ Gem of 37.5 pc). However, without precise astrometric data, it is impossible to determine whether the radio emission is coincident with one or both of the stars at the time of the observations. Possible models for the generation of radio emission in chromospherically active stars include phenomena such as gyro-synchrotron radiation from polar-cap regions of the active K-giant–type star, emission at the tops and/or feet of one or more coronal loops originating on the K-giant, and emission from active regions or hot spots near the surface of both stars in the binary, with possible channeling of energetic electrons from the K-giant to the surface of the smaller companion star along interconnecting magnetic field lines.

For systems such as σ Gem, SIM Lite will provide positional information on the 10 μas level and the three-dimensional orbit for the binary. As a pointed mission, SIM Lite will have the flexibility to coordinate observations with other instruments such as the Very Large Baseline Array (VLBA) to allow the

Figure 12-5. A total intensity contour map of the radio emission from the RS CVn binary system σ Geminorum. The peak flux density is ~55 mJy. The system is composed of a K-giant primary and an unseen companion. The spectroscopically determined major axis of the orbit is $2\ a \sin(i) = 0.13$ AU (~3.4 mas at 37.5 pc). The relative separation between the two radio components is ~3.4 mas. SIM Lite's wide-angle measurement accuracy has to be magnified 50 times to be presented on the scale of this map.




registration of the radio emission relative to the system components for systems with orbital periods on the order of days. This more complete picture of the system will, in turn, help to distinguish between the various mechanisms by which the radio emission is generated.

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