We present a novel technique to determine the absolute inclination of single stars using multi-wavelength sub-milliarcsecond astrometry. The technique exploits the effect of gravity darkening, which causes a wavelength-dependent astrometric displacement parallel to a star’s precessed rotation axis. We find that this effect is clearly detectable using SIM Lite for various giant stars and rapid rotators, and present detailed models for multiple systems using the REFLUX code. We also explore the multi-wavelength astrometric reflex motion induced by spots on single stars. We find that it should be possible to determine spot size, relative temperature, and some positional information for both giant and nearby main-sequence stars utilizing multi-wavelength SIM Lite data. These data will be extremely useful in stellar and exoplanet astrophysics, as well as supporting the primary SIM Lite mission through proper multi-wavelength calibration of the giant star astrometric reference frame, and reduction of noise introduced by starspots when searching for extrasolar planets.

Key words: astrometry – stars: fundamental parameters

Online-only material: color figures

1. INTRODUCTION

SIM Lite is currently expected to have ~80 spectral channels (Davidson et al. 2009), spanning 450–900 nm, thus allowing multi-wavelength microarcsecond astrometry, which no current or planned ground- or space-based astrometric project (GAIA, CHARA, VLT/PRIMA, etc.) is able to match. We showed in our first paper (Coughlin et al. 2010), hereafter referred to as Paper I, the implications multi-wavelength microarcsecond astrometry has for interacting binary systems. In this paper, we discuss an interesting effect we encountered while modeling binary systems, namely, that gravity darkening in stars produces a wavelength-dependent astrometric offset from the center of mass that increases with decreasing wavelength. It is possible to use this effect to derive both the inclination and gravity-darkening exponent of a star in certain cases.

Determining the absolute inclination of a given star has many practical applications. There is much interest in the formation of binary stars, where whether or not the spin axis of each star is aligned with the orbital axis provides insight into the planet's formation history of the system (Turner et al. 1995). The mutual inclination between the stellar spin axes and the orbital axis can greatly affect the rate of precession, which is used to determine the inclination axis from each method, confirming or refuting the asteroseismic models and spectro-interferometric and RM measurements. We also explore the multi-wavelength astrometric reflex motion induced by spots on single stars. We find that it should be possible to determine spot size, relative temperature, and some positional information for both giant and nearby main-sequence stars utilizing multi-wavelength SIM Lite data. These data will be extremely useful in stellar and exoplanet astrophysics, as well as supporting the primary SIM Lite mission through proper multi-wavelength calibration of the giant star astrometric reference frame, and reduction of noise introduced by starspots when searching for extrasolar planets.

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stellar limb darkening) is critical to accurately deriving the co-
inclination from the RM effect, as well as other quantities in
stellar and exoplanet astrophysics.

In this paper, we also present models for multiple systems
and discuss the determination of spot location, temperature, and
size on single stars, which produce a wavelength-dependent
astrometric signature as they rotate in and out of view. Starspots
are regions on the stellar surface where magnetic flux emerges
from bipolar magnetic regions, which blocks convection and
thus heat transport, effectively cooling the enclosed gas, and thus
are fundamental indicators of stellar magnetic activity and the
internal dynamos that drive it. İsık et al. (2007) discuss how the
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internal dynamos that drive it. İsık et al. (2007) discuss how the
observation of spot location, duration, stability, and temperature
can probe the stellar interior and constrain models of magnetic
flux transport. Through the observation of the rotation rates of
starspots at varying latitudes, one is able to derive the differential
rotation rate of the star (Collier Cameron 2002), which may be
directly related to the frequency of stardust cycles. Mapping
spots in binary star systems provide insight into the interaction
between the magnetic fields of the two components, which can
cause orbital period changes (Applegate 1992), radii inflation
(López-Morales 2007; Morales et al. 2008), and may possibly
explain the ~2–3 hr period gap in cataclysmic variable systems
(Watson et al. 2007). Detecting and characterizing starspots via
multi-wavelength astrometry would be complementary to other
existing techniques, namely, optical interferometry (Wittkowski
et al. 2002), tomographic imaging (Donati et al. 2006; Aurière
et al. 2008), photometric monitoring (Alekseev 2004; Mosser
et al. 2009), and in the future, microlensing (Hwang & Han
2010).

We present the details of our modeling code, reflux, in
Section 2, discuss the inclination effect and present models for
multiple stars in Section 3, discuss the spot effects and present
models in Section 4, and present our conclusions in Section 5.

2. THE REFLUX CODE

Reflux4 is a code that computes the flux-weighted astro-
metric reflex motion of binary systems. We discussed the code in
detail in Paper I, but in short, it utilizes the Eclipsing Light
Curve (ELC) code, which was written to compute light curves
of eclipsing binary systems (Orosz & Hauschildt 2000). The
ELC code represents the surfaces of two stars as a grid of indi-
vidual luminosity points, and calculates the resulting light curve
given the provided systemic parameters. ELC includes the dom-
inant physical effects that shape a binary’s light curve, such as
non-spherical geometry due to rotation, gravity darkening, limb
darkening, mutual heating, reflection effects, and the inclusion
of hot or cool spots on the stellar surface. For the work in this
paper we have simply turned off one of the stars, thus allowing
us to probe the astrometric effects of a single star. To compute
intensity, ELC can either use a blackbody formula or interpolate
from a large grid of NextGen model atmospheres (Hauschildt
et al. 1999). For all the simulations in this paper, we have used
the model atmosphere option, and will note now, and discuss in
more detail later, that the calculation of limb darkening is auto-
matically included in NextGen model atmospheres. These arti-

cialized derived limb-darkening coefficients have recently been
shown to be in error by as much as ~10%–20% in comparison to
observationally derived values (Claret 2008), and thus their

3. INCLINATION AND ROTATION

The astrophysical phenomenon of gravity darkening, also
sometimes referred to as gravity brightening, is the driving
force behind the ability to determine the inclination of a
single star using multi-wavelength astrometry. A rotating star
is geometrically distorted into an oblate spheroid, such that its
equatorial radius is greater than its polar radius, and thus the
poles have a higher surface gravity, and the equator a lower
surface gravity, than a non-rotating star with the same mass
and average radius. This increased surface gravity, g, at the
poles results in a higher effective temperature, T_eff, and thus
luminosity; decreased g at the equator results in a lower T_eff and
luminosity. This temperature and luminosity differential cause
the star’s center of light, or photocenter, to be shifted toward
the visible pole, away from the star’s gravitational center of
mass. Since the inclination determines how much of the pole
is visible, the amount of displacement between the photocenter
and the center of mass is directly related to the inclination.
Furthermore, since the luminosity difference effectively results
from a ratio of blackbody luminosities of differing temperatures,
the effect is wavelength dependent, with shorter wavelengths
shifted more than longer wavelengths. Thus, the amount of
displacement between the measured photocenter in two or more
wavelengths is directly related to the inclination. See Figure 1
for an illustration of the effect.

An additional complicating factor is the exact dependence
of temperature on local gravity, von Zeipel (1924) was the first
to derive the quantitative relationship between them, showing
that \( T^4 \propto g^{\beta_1} \), where \( \beta_1 \) is referred to as the gravity-darkening exponent. The value of \( \beta_1 \) has been a subject of much study and
debate; for a complete review, see Claret (2000), who presents
both an excellent discussion of past studies, as well as new,
detailed computations of \( \beta_1 \) using modern models of stellar
atmospheres and internal structure that encompass stars from
0.08 to 40 M_\odot. Since the value of \( \beta_1 \) affects the temperature
differential between equator and pole, the multi-wavelength
displacement will also be dependent on the value of \( \beta_1 \). The
total amplitude of the effect will be scaled by the angular size of
the star, which depends on both its effective radius and distance.
Thus, in total, the components of this inclination effect are the
effective stellar radius, distance, effective temperature, rotation
rate, \( \beta_1 \), and inclination of the star. In principle, one is able
to determine the effective stellar radius, effective temperature,
rotation rate, and distance of a target star using ground-
based spectroscopy and space-based parallax measurements,
including from SIM Lite. Thus, when modeling the multi-

4 reflux can be run via a web interface from
http://astronomy.nmsu.edu/jlcough/reflux.html. Additional details as to how to
set up a model are presented there.
Figure 1. Illustration of the inclination effect using brightness maps of Capella Ab, which has an inclination of 42.788° (Torres et al. 2009). Left: Capella Ab artificially spun-up to near its break-up speed to accentuate the gravity-darkening effect for ease of viewing. As can be seen, the photocenter of the system is dramatically shifted away from the center of mass, toward the visible pole, which is brighter than the rest of the star due to gravity darkening. Furthermore, since the pole is physically hotter, the $U$-band photocenter is shifted more than the $K$-band photocenter, and in the direction of the projected rotation axis or the $y$-axis. Right: Capella Ab at its actual rotation period. As can be seen, the actual effect is small compared to the angular size of the star on the sky, but still large compared to the 1 μas benchmark of SIM Lite. The presence of limb darkening is clearly visible, which causes a decrement in flux toward the limb of the star. Note that the broad wavelength coverage of SIM Lite will only cover the $B$, $V$, $R$, and $I$ bandpasses. (A color version of this figure is available in the online journal.)

Table 1
Parameters for Capella Aa

| Parameter                  | Value^a |
|----------------------------|---------|
| Distance (pc)              | 12.9    |
| Rotation period (days)     | 106.0   |
| Mass ($M_\odot$)           | 2.70    |
| Radius ($R_\odot$)         | 12.2    |
| Effective temperature (K)  | 4940    |
| $\beta_1$                 | 0.43    |

Note. ^a Values from Torres et al. (2009).

Table 2
Parameters for Capella Ab

| Parameter                  | Value^a |
|----------------------------|---------|
| Distance (pc)              | 12.9    |
| Rotation period (days)     | 8.64    |
| Mass ($M_\odot$)           | 2.56    |
| Radius ($R_\odot$)         | 9.2     |
| Effective temperature (K)  | 5700    |
| $\beta_1$                 | 0.39    |

Note. ^a Values from Torres et al. (2009).

Table 3
Parameters for Vega

| Parameter                  | Value^a |
|----------------------------|---------|
| Distance (pc)              | 7.76    |
| Rotation period (days)     | 0.521   |
| Mass ($M_\odot$)           | 2.11    |
| Radius ($R_\odot$)         | 2.5     |
| Effective temperature (K)  | 9602    |
| $\beta_1$                 | 1.02    |

Note. ^a Values from Aufdenberg et al. (2006) and Peterson et al. (2006).
Figure 2. Astrometric displacement of each bandpass with respect to $K$ band vs. inclination for Capella Aa. Dashed lines are a model with $\beta_1$ decreased by 10%. Due to the slow rotation rate of Capella Aa, the effect is limited to a maximum of $\sim2.0$ $\mu$as between $U$ and $K$ bands, and only a maximum of $\sim0.7$ $\mu$as between $B$ and $I$ bands, where $SIM$ Lite will operate. This puts the detection of this effect for Capella Aa at the very edge of $SIM$ Lite’s capability.

(A color version of this figure is available in the online journal.)

Figure 3. Astrometric displacement of each bandpass with respect to $K$ band vs. inclination for Capella Ab. Dashed lines are a model with $\beta_1$ decreased by 10%. Due to the fast rotation rate of a Capella Ab like star, the effect is moderate with tens of microarcseconds of displacement, and thus these types of stars are excellent targets for $SIM$ Lite. The actual inclination of Capella Ab is $42.788^\circ$ (Torres et al. 2009), and thus Capella Ab itself should show a large shift of the photocenter with wavelength. Note that the broad wavelength coverage of $SIM$ Lite will only cover the $B$, $V$, $R$, and $I$ bandpasses. (A color version of this figure is available in the online journal.)

Our modeling confirms this, showing a total $U$–$K$ amplitude of $\ll0.1$ $\mu$as for a $1.0$ $M_\odot$, $1.0$ $R_\odot$ star with a rotation period of 30.0 days at 10.0 parsec. These conclusions on detectability are made with the assumption that, for bright stars like these, $SIM$ Lite can achieve its microarcsecond benchmark. We show that this is possible in a narrow angle (NA) mode by employing the
SIM Differential Astrometry Performance Estimator (DAPE; Plummer 2009). For a target star with magnitude $V = 5$, and a single comparison star with $V = 10$ located within a degree of it on the sky, by integrating 15 s on the target, and 30 s on the reference, for 10 visits at five chop cycles each, a final precision of $\pm 1.01$ µas is achieved in only 1.04 hr of the total mission time. For a fainter target with $V = 10$, this precision is only reduced to $\pm 1.32$ µas in the same amount of mission time. In utilizing NA mode, one must be careful in choosing the reference star(s) to ensure that they are not stars with a substantial wavelength-dependent centroid. Given the only constraints on reference stars are that they need to have $V \lesssim 10$ and are within 1° on the sky, one could easily choose a slow-rotating, main-sequence star, determined as such via ground-based observations as a wavelength-independent astrometric reference star. We also note that wide angle SIM Lite measurements, with a precision of ~5 µas, may not detect the wavelength-dependent photocenter of a system like Capella, but will have no difficulty detecting it in stars like Capella Ab or Vega.

The effect of decreasing the gravity-darkening exponent is to decrease the total amplitude of the effect in each wavelength, with shorter wavelengths affected more than longer wavelengths. Thus, the choice of gravity-darkening exponent is intimately tied to the derived inclination. If one were to model observed data with a gravity-darkening exponent that was ~10% different than the true value, one would derive an inclination that would also be ~10% different from the true inclination. However, the two combinations of inclination and gravity-darkening exponent do not produce identical results, and can be distinguished with a sufficient precision at a number of wavelengths. For example, if one were to adopt the nominal value for $\beta_1$ and derive an inclination of 40° for a Vega-like star, then adopt a $\beta_1$ value that was 10% lower, one would derive an inclination of 43°, a 7.5% change. In this case though, with the lower $\beta_1$ value, the measured photocenter in the $U, B, V, R, I, J,$ and $H$ bandpasses, with respect to the $K$-band photocenter, would differ from the nominal $\beta_1$ model by $\sim 0.5, -1.0, -2.0, -2.0, -1.6, -1.0, and 0.2$ µas, respectively. Note that for $B, V, R,$ and $I,$ where SIM Lite can observe, these discrepancies, on the order of $\sim 1$ µas, should be large enough to be distinguished in the NA mode. Thus, a unique solution exists for the values of $i$ and $\beta_1$ if the photocenter is measured in three or more wavelengths. (The photocenter of one wavelength is used as a base measurement, with respect to which the photocenters of other wavelengths are measured. If one measures the photocenter in three or more wavelengths, one then has two or more differential photocenter measurements, and can then solve for the two unknown variables. Although we have chosen the $K$ band as the base measurement in our models, simply because it is the longest wavelength we model and thus shows the least variation, one could easily choose another band, such as $R,$ where SIM Lite will be able to observe. In the example just given of possible degeneracy between inclination and $\beta_1,$ if one chose the $R$ band as the base measurement, one would still detect a difference of $\sim 1$ µas between the $B$ and $V$ photocenters, and be able to resolve the degeneracy between inclination and $\beta_1.$)

Another complication is the possibility of having equally good fitting high and low solutions for $i.$ For example, if one observed and determined a best-fit inclination of 70° for a Vega-like star, one could obtain a reasonably good fit as well at 46°, (see Figure 4). However, just as in the case of the uncertainty in the value of $\beta_1,$ discernible discrepancies would exist. In this case, the discrepancies in the measured photocenter in the $U, B, V, R, I, J,$ and $H$ bandpasses, with respect to the $K$-band

![Figure 4](https://example.com/figure4.png)

Figure 4. Astrometric displacement of each bandpass with respect to $K$ band vs. inclination for Vega. Dashed lines are a model with $\beta_1$ decreased by 10%. Note that due to the very fast rotation of Vega, along with a high value of $\beta_1$, the effect can be quite large, at a couple of hundred microarcseconds. For a Vega-like star, SIM Lite observations would yield very accurate values for $\beta_1$ and the inclination. For Vega itself, which is known to be nearly pole on, with an inclination of 5:7 (Hill et al. 2010), there should be a $B$-band minus $I$-band displacement of 6.0 µas, still detectable by SIM Lite. Note that the broad wavelength coverage of SIM Lite will only cover the $B, V, R,$ and $I$ bandpasses.

(A color version of this figure is available in the online journal.)
photocenter, would be −0.1, −9.0, −2.0, 1.5, 6.0, 1.0, and 0.2 μas, respectively. Just as in the case of the uncertainty in the value of $\beta_1$, this discrepancy between equally good fitting high- and low-inclination solutions can be resolved if one has three or more wavelengths obtained in the NA mode.

As mentioned in Section 1, we note that the limb-darkening function, which was automatically chosen by the ELC code as incorporated into the model atmospheres, can differ from actual observed values by ∼10% (Claret 2008). We have tested how changing the limb-darkening coefficients by 10% affects the resulting astrometric displacements, and find that the result is less than 0.5% for all wavelengths, and thus is negligible in the modeling. The reason is that limb darkening is symmetric, and thus while increased limb darkening damps the visible pole, it also damps the rest of the star, and thus the relative brightness between regions is maintained.

Additionally, this inclination technique yields the orientation of the projected stellar rotation axis on the sky, which is parallel to the wavelength dispersion direction. When coupled with the derived inclination, this technique thus yields the full three-dimensional orientation of the rotation axis. This could be a powerful tool in determining the overall alignment of stellar axes in the local neighborhood and in nearby clusters.

4. STARSPOtS

Another area of astrophysical interest to which multi-wavelength astrometric measurements from SIM Lite can contribute is the study of starspots. As the cause of starspots are intense magnetic fields at the photosphere, they are typically found in stars with convective envelopes, especially rapidly rotating stars. Thus, both low-mass, main-sequence K and M dwarfs, as well as rapidly rotating giant and sub-giant stars, are known to host large spots on their surface. The study of the distribution, relative temperature, and size of these spots would greatly contribute to the study of magnetic field generation in stellar envelopes. A starspot that rotates in and out of view will cause a shift of the photocenter for a single star, which has been a subject of much recent discussion in the literature (e.g., Hatzes 2002; Unwin 2005; Eriksson & Lindegren 2007; Catanzarite et al. 2008; Makarov et al. 2009; Lanza et al. 2008), especially in light of its potential to mimic, or introduce noise when characterizing, an extrasolar planet. However, there has been no mention in the literature of the multi-wavelength astrometric signature of stellar spots, where, just as in the case of the gravity-darkening inclination effect, we are looking at essentially two blackbodies with varying temperatures, and thus shorter wavelengths will be more affected by a spot than longer wavelengths.

To characterize the multi-wavelength astrometric signature of stellar spots, we model two spotty systems, again using the reFLUX code. We model Capella Ab, which shows evidence of large spots and is suspected of being an RS CVn variable (Hummel et al. 1994), and a typical main-sequence K dwarf. For Capella Ab, we use the parameters listed in Table 2, along with the star’s determined inclination of 42° (Torres et al. 2009), and add a cool spot that has a temperature that is 60% of the average surface temperature, located at the equator, at a longitude such that it is seen directly at phase 270°, and having an angular size of 10° (where 90° would cover exactly one half of the star). For the K dwarf system, we use the physical parameters listed in Table 4, simulating a typical K Dwarf at 10 pc, and add a cool spot with the same parameters as we do for Capella Ab. Additionally, to investigate the effects of cool versus hot spots or flares, we also run a model with a hot spot by changing the spot temperature to be 40% greater than the average surface temperature. We present our models in Figures 5–7.

As can be seen for Capella Ab, the gravity-darkening inclination effect presented in Section 3 dominates the spread of colors in the $y$-direction, the direction parallel to the stars’ projected rotation axis. However, the amplitude of the spot motion is quite large, with a total amplitude of ∼40 μas in all bandpasses, which would be easily detectable by SIM Lite. For the K dwarf with a cool spot, we see a much smaller, but still detectable shift of amplitude ∼5–8 μas, depending on the wavelength. In the case of a hot spot or flare, we see a much larger displacement, on the order of ∼10–200 μas, depending on the wavelength, which would be easily detectable by SIM and provide extremely precise values in deriving the spot parameters.

In general, the temperature of the spot, in relation to the mean stellar surface temperature, is related to the spread in observed wavelengths, with a larger spread indicating a larger temperature difference. The duration of the astrometric displacement in phase, coupled with the overall amplitude of the astrometric displacement, yields the size of the spot, as larger spots will cause larger displacements and be visible for a larger amount of rotational phase. The latitude of the spot can also affect the total duration. Finally, the amplitude of the astrometric displacement in the $x$ direction versus the $y$ direction is dependent on both the latitude of spot and the inclination of the star. Thus, when modeled together, one is able to recover these parameters. This work can also be combined with our work in Paper I to derive the location of spots in binary systems, as the astrometric signature of the spot is simply added to the astrometric signature of the binary system.

The astrometric motion induced upon a parent star by a host planet does not have a wavelength dependence. Spots however, as we have shown via our modeling, have a clear wavelength dependence. Thus, if one has a candidate planetary signal from astrometry, but it shows a wavelength-dependent motion, it must then be a false positive introduced from starspots at the rotation period of the star (assuming that the planet’s emitted flux is negligible compared to the star). Furthermore, when SIM is launched, there will likely be many cases where a marginally detectable signal due to a planetary companion is found at a very different period than the rotation period of the star. However, starspots will still introduce extra astrometric jitter which will degrade the signal from the planetary companion. Multi-wavelength astrometric data can be used to model and remove the spots, which will have a wavelength dependence, and thus strengthen the planetary signal, which will not have a wavelength dependence.

| Table 4 | Parameters for the K Dwarf System |
|---------|----------------------------------|
| Parameter | Value |
| Distance (pc) | 10.0 |
| Inclination (°) | 60.0 |
| Period (days) | 10 |
| Mass (M⊙) | 0.6 |
| Radius (R⊙) | 0.6 |
| Effective temperature (K) | 4500 |
| Latitude of spot (°) | 90 |
| Longitude of spot (°) | 270 |
| Angular Size of Spot (°) | 10 |
| Cool spot temperature factor | 0.6 |
| Hot spot temperature factor | 1.4 |
Figure 5. Simulated cool spot on Capella Ab. The spot is located on the equator, with a longitude such that it is seen directly at phase 270°. The strong presence of the gravity-darkening effect, discussed in Section 3, dominates the wavelength spread in the y direction. Note that the broad wavelength coverage of SIM Lite will only cover the B, V, R, and I bandpasses. (A color version of this figure is available in the online journal.)

Figure 6. Simulated cool spot on a nearby K dwarf star with an inclination of 60°, whose parameters are given in Table 4. The spot is located on the equator, with a longitude such that it is seen directly at phase 270°. Note that the broad wavelength coverage of SIM Lite will only cover the B, V, R, and I bandpasses. (A color version of this figure is available in the online journal.)

Figure 7. Simulated hot spot or flare on a nearby K dwarf star with an inclination of 60°, whose parameters are given in Table 4. The spot is located on the equator, with a longitude such that it is seen directly at phase 270°. Note that the broad wavelength coverage of SIM Lite will only cover the B, V, R, and I bandpasses. (A color version of this figure is available in the online journal.)
5. DISCUSSION AND CONCLUSION

We have presented detailed models of the multi-wavelength astrometric displacement that SIM Lite will observe due to gravity darkening and stellar spots using the REFLEX code. We find that SIM Lite observations, especially when combined with other techniques, will be able to determine the absolute inclination, gravity-darkening exponent, and three-dimensional orientation of the rotational axis for fast- and slow-rotating giant stars and fast-rotating main-sequence stars. This technique will be especially useful in probing binary star and exoplanet formation and evolution, as well as the physics of star-forming regions. Direct observational determination of the gravity-darkening exponent has direct applications in both stellar and exoplanet astrophysics. This technique is also relatively inexpensive in terms of SIM Lite observing time, as one need only to observe a given star once, as opposed to binary stars and planets, which require constant monitoring over an entire orbit. It should be noted that this effect should be taken into account when constructing the SIM Lite astrometric reference frame, such that fast-rotating giants should be excluded so as not to produce a wavelength-dependent astrometric reference frame.

We have also presented models of starspots on single stars and find that SIM Lite should be able to discern their location, temperature, and size. Combined with other techniques, this will provide great insight into stellar differential rotation, magnetic cycles and underlying dynamos, and magnetic interaction in close binaries. From this modeling, it should especially be noted that multi-wavelength astrometry is a key tool in the hunt for close binaries. From this modeling, it should especially be noted that multi-wavelength astrometry is a key tool in the hunt for close binaries.

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