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THE OPPORTUNITIES AND CHALLENGES FOR ASTROMETRY IN THE 21ST CENTURY

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RESUMEN

Con el advenimiento de las posiciones, paralajes y movimientos con precisiones de micro segundos de arco, la Astrometría y la Mecánica Celeste han entrado a una nueva era. Los avances recientes en las técnicas de radio-interferometría y los obsevatorios ópticos en órbita ya programados han hecho posible abordar problemas científicos de frontera que estaban fuera de nuestro alcance hace apenas unos años. Pronto será posible determinar de manera definitiva las distancias a las cefeidas y RR Lyras, al centro de la Galaxia, a las Nubes de Magallanes y a otras galaxias del Grupo Local. Podremos medir los parámetros orbitales de las galaxias enanas que se están fusionando con la Vía Láctea, definir mejor la cinemática, dinámica y estructura de nuestra Galaxia y buscar evidencia de la materia oscura que constituye la mayor parte de la masa del Universo. Se podrá determinar las masas de las estrellas con menos del 1% de error, con lo cual tendremos manera de comprobar en detalle las teorías sobre evolución estelar. También podremos obtener soluciones completas para las órbitas de los sistemas planetarios extra-solares. Pronto se construirán además grandes telescopios terrestres para medir posiciones, paralajes y movimientos propios con precisiones de mili segundos de arco. Estos instrumentos, si bien más limitados, producirán enormes cantidades de datos, con lo cual será posible estudiar la distribución espacial y cinemática de las estrellas llegando a magnitudes mucho más débiles que los observatorios espaciales.

ABSTRACT

Astronometry and Celestial Mechanics have entered a new era with the advent of Micro-arcsecond positions, parallaxes and proper motions. Recent advances in radio interferometric techniques and the scheduled space-based optical observatories have made it possible to address cutting-edge science topics that were far beyond our grasp only a few years ago. It will soon be possible to determine definitive distances to Cepheid and RR Lyrae variables, the center of our Galaxy, the Magellanic Clouds and other Local Group members. We will measure the orbital parameters of dwarf galaxies that are merging with the Milky Way, define the kinematics, dynamics and structure of our Galaxy and search for evidence of the Dark Matter that makes up most of the mass in the universe. Stellar masses will be determined routinely to 1% accuracy so that detailed test of stellar evolution theory can finally be made and we will be able to make full orbit solutions and mass determinations for Extrasolar planetary systems. Very large ground-based telescopes will soon be built to measure positions, parallaxes and proper motions at the milli-arcsecond level. These ground-based telescopes, while more limited in accuracy, will produce enormous amounts of data and enable us to study the spatial and kinematical distributions of stars to much fainter magnitudes than the space observatories.

Key Words: astrometry — reference systems

1. INTRODUCTION

Advances in astrometry have always been driven by technology. From the earliest days the accuracy of our positions were limited by the resolution of our eye, Quadrant murals, telescopes, photographic plates, optical and radio interferometers, automatic measuring machines, CCD cameras and space satellites. In addition, our ability to analyze those observations has been limited by the computational power of our computers, both human and now electronic. We have entered the 21st century and the age of micro-arcsecond (μas) astrometry with the new results from the VERA radio interferometric array (Honma et al. 2007) and look forward to reaching those levels in optical astrometry in the next decade with the soon to be launched Gaia, JASMINE, SIM and OBSS satellites. In the meantime, ground-based optical interferometers are moving towards micro-arcsecond relative positions and CCD mosaic cameras on medium-sized telescopes are offering enormous amounts of data with milli-arcsecond (mas) relative positions. These technological advances will make it possible to do research at the forefront of as-

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TABLE 1

ACCURACY ESTIMATES AND CHARACTERISTICS OF SOME ASTROMETRIC PROJECTS

Positional accuracy	Technology	Parallax	Proper motion	Limitations
2 mas now	WIYN I-band & OT CCD	660 uas	540 uas/y	V, I<20, 26 obs., fwhm=0.6"
1 mas 2010	WIYN Z-band & OTA CCD	330 uas	270 uas/y	Z < 22, fwhm = 0.35" 26 obs., 4 obs. 2 yrs later
6 uas 2020	Gaia V < 15	21 uas	11 uas/y	Mission accuracy, sigma = f(mag)
	V < 20	275 uas	145 uas/y	
4 uas 2020?	SIM V < 20, 15d	4 uas	2.5 uas/yr	Mission accuracy, sigma = f(field of view)
	1 degree fov	1 uas	0.6 uas/y	

tronomy using astrometric techniques in a way never before possible. In this paper I will review some of the instrumentation advances that will make this new era of astrometry possible and highlight some of the science that will become a part of astrometric research.

2. ASTROMETRY AND TECHNOLOGY

We had our first taste of large-scale high-accuracy astrometry in the optical part of the spectrum with the launch of the Hipparcos satellite (Perryman 2008), which initially produced positions and parallaxes for fairly bright stars at the one-mas level and with refinement the accuracy for some stars is 0.5 mas or better (van Leuuven 2007). The Hubble Space Telescope Fine Guidance Sensors made it possible to obtain relative parallaxes to approximately 0.2 mas accuracy for a small number of fainter stars of special astrophysical interest (Benedict et al. 2008). Ground-based interferometers continue to provide relative positions at the mas level or better for small numbers of carefully selected stars in very small fields of view. However, our future in the micro-arcsecond arena lies with space astrometry and our expectations for Gaia, JASMINE, SIM and OBSS. It must be stressed that not all high-accuracy astrometry in the future will be done by any one of the space satellites. Each has its niche: Gaia for all stars brighter than magnitudes 15, SIM for a few stars with the highest levels of accuracy and objects as faint as magnitude 20, JASMINE for detailed studies of the galactic bulge, and OBSS to extend Gaia's accuracy to stars fainter than SIM's limit of 20.

3. THE EARTH'S ATMOSPHERE

The atmosphere of the Earth acts like a corrugated wave front that distorts the image shape and displaces a star from its true position. Fortunately, the image degradation acts nearly like a Gaussian broadening function, which makes it easier for us to model the point-spread function of the stars that we observe. Due to the corrugated wave front, two stars that are very close to each other have their positions displaced by nearly the same amount and therefore their relative positions are essentially unchanged. As a consequence, the accuracy of relative positions is much better than that of the individual positions.

For example, 30 seconds of exposure on two stars separated by 10 arcminutes will yield an accuracy of about 7 mas in their separation, while if the same two stars were separated by only 2 arcseconds the accuracy of their separation might be as small as one mas. This example offers a partial solution to our problem. If one of the pair of stars can be used as a guide star and we can guide sufficiently rapidly to track the atmospheric motions, then the second star and those surrounding it will have their relative positional shifts reduced. This approach is usually called "first-order adaptive optics", or "tip-tilt correction". Full adaptive optics involves being able to map the shape of the corrugations in real time and distorting a flexible transfer mirror to compensate for the atmospheric corrugations; however, it is a very costly approach. At a good observing site the correlation between the atmospheric shifts experienced by two stars separated by 4 arcminutes is reduced to about 50%, i.e. half of the time the two stars will be shifted in the same direction. This limitation in the field size for the tip-tilt method means that in order to achieve larger fields of view we must use multiple guide stars, which is an approach developed by Tonry et al. (1997) and implemented on the Orthogonal-Transfer CCD's. Large-scale implementation of OT CCD's into arrays has yielded Orthogonal-Transfer Arrays, or OTA's that are being used with the PanSTARRS (Kaiser et al. 2002) and WIYN One-Degree Imager (ODI) as described by Jacoby (2002). The accuracy estimates for the ODI listed in the first two rows of Table 1 are from Vieira, Girard, & van Altena (2006) and are based on measurements made with the Tonry et al. (2004) OPTIC camera, which uses the OT CCD's on the WIYN 3.5 m telescope. The use of this new technology will revitalize ground-based astrometry, especially since its use on medium-aperture telescopes yields much fainter limiting magnitudes than will be achievable from space, due to the limited aperture sizes that can now be built and launched.

4. GROUND-BASED SCIENCE OPPORTUNITIES

4.1. *Photometric surveys provide finding lists for astrometric research*

Given the impressive increases in astrometric accuracy made possible by the OTA technology and its application to the large gigapixel cameras such as the WIYN ODI camera, we now look at some of the science that we will be able to undertake. This is selection is biased by my personal interests, but it gives some perspective on the possibilities for research in the near future. The starting point for many of these projects are the all-sky surveys recently made with small telescopes such as the 2MASS infrared survey (Cutri et al. 2003), the southern DENIS infrared survey (2005), the SDSS multi-band visible survey (Adelman-McCarthy et al. 2007, 2008), the INT-WFS survey (Irwin et al. 2005), etc. The value of these photometric surveys is that they enable one to search for groups of stars with possible common origin in color-magnitude arrays and then to determine their proper motions using our new technology to see if the stars are in fact moving with common proper motions, or determine the mean motion of the stars if we already have reason to believe that they are physically associated.

4.2. *Determining the orbits of satellite galaxies*

One such example is the study by Dinescu et al. (2005) of the Sgr dwarf galaxy that is merging with the Galaxy. Previous photometric studies identified potential members of the Sgr dwarf and the radial velocities of those stars were determined leading to a number of possible orbit solutions. The determination of the proper motions of those stars then leads to a measurement of the tangential velocity of the Sgr dwarf and a definitive orbit. Several other possible merging dwarf galaxies are known and a determination of their proper motions would help us to understand the dynamics of their orbital evolution.

4.3. *Discovering dwarf galaxies merging with the Milky Way*

A related problem concerns the currently accepted Lambda cold-dark matter cosmological models that predict several hundred merging dwarf galaxies within one kiloparsec of the Sun (Helmi & White 1999). Unfortunately only a handful of possible candidates have been identified, which casts doubt on the validity of the model. An alternative possibility is that we have not been able to discover those faint objects. Johnston, Spergel, & Hayden (2002) predict that the velocity dispersion will be 5 km s^{-1} or less for the remnants of merging dwarfs. Using the estimates of the proper motion accuracy in Table 1 for the WIYN ODI we predict that an intensive survey of about 100 square degrees should reveal the presence of about 20–30 streams within about 2 kpc, if they exist. If that number of streams is not identified, then something is clearly amiss with the Lambda CDM model.

4.4. *Searching for Dark Matter in the disk of the Galaxy*

The amount of "Dark Matter" in the local disk is still in dispute. Different surveys give conflicting results, although there may be some convergence towards the amount of Dark Matter being small, e.g. Girard et al. (2006). Using the same survey referred to in the previous paragraph we can determine the parallaxes of all stars in the survey regions with an accuracy of about 0.5 mas for stars as faint as magnitude 21. This faint limiting magnitude will enable us to observe all of the brown dwarfs, L & T dwarfs in the survey area within 150 pc, i.e. a complete inventory of the stellar density with an accuracy of 2% will be made. In combination with the relatively small percentages of gas and dust in the solar neighborhood, we should then have a complete census of the local mass. That inventoried mass can then be compared to the dynamical mass inferred from radial velocity surveys of the vertical velocity distribution to yield the differential mass, or amount of Dark Matter.

4.5. *Using star clusters as laboratories for stellar evolution*

Star clusters provide us with laboratories to study the formation and evolution of stars, since we have good reason to believe that the stars in a cluster formed from the same cloud of gas and all have approximately the same metal content and age. The only major variable left is the stellar mass, which then gives us the perfect opportunity to study the luminosity and temperature changes as a function of mass for a given age and metalicity. Unfortunately, we observe the stars in a cluster against foreground and background contaminating stars. To be sure that the conclusions drawn from the analyses are valid and not due to having measured a star that is not a member of the cluster, we need to eliminate all of the non-members from the sample. By measuring the relative proper motions of the stars in the field of the cluster we can identify stars not moving with the motion of the cluster using techniques described, for example, by Vasilevskis, Klemola, & Preston (1958) and Platais et al. (2003). In the past it was necessary to wait 20 to 30 years after the first-epoch plates were taken to repeat them and determine the proper motions. However, with the new technology we can repeat the exposures after only two years. The advantage here is that not only can the study be completed in a relatively short time, but the main limitation in the past was that the old plates had a bright limiting magnitude and the interesting faint and low mass stars were beyond the old plate limit. Now we can carry out these studies in a two-year time span to magnitude 22, or by extending the exposure time a bit to even fainter magnitudes.

4.6. *Measuring the masses of black holes and stars*

Black holes can be the final state of cataclysmic collapse of massive stars as well as a consequence of dynamical friction in the centers of galaxies where multitudes of stars spiral into a common gravitational center. Questions abound concerning the masses of these black holes and some estimates exist from spectroscopic measurements of the widths of spectral lines in the integrated spectra of the cores of those galaxies that are interpreted as being due to the velocities of stars in dynamical equilibrium with the massive black hole. Astrometric measurements of the orbits of stars around the black hole in the center of the Galaxy have recently become available through the application of adaptive optics in the infrared. Over the course of the past decade Genzel et al. (1997) and UCLA (Ghez 2008) have measured the orbital parameters of several massive stars as they orbit the center of the Galaxy. Remarkably, by observing in the infrared they can observe through 20 visual magnitudes of obscuration and directly determine the mass of the central object to be about three million solar masses and with great certainty infer that the massive object is a black hole and not a cluster of neutron stars or some other kind of massive objects.

Similarly, the masses of stars can be measured with increasing accuracy by observing the interference of light after it passes through the atmosphere's corrugated wave front. Using the technique of Speckle Interferometry (Laberyie 1970), multiple very short exposures are combined in a computer to achieve diffraction-limited resolution and measure the separation and position angles of close binary stars. Extension of that technique to simultaneous observations at two wavelengths, has now made it possible to reach one-quarter of the diffraction limit of the telescope (Horch, Franz, & van Altena 2006). As a result, we can now determine accurate masses of stars for a comparison with stellar evolutionary models that is limited only by the accuracy of the parallaxes, i.e. we are waiting for Gaia and SIM to give us definitive parallaxes that will yield 1% masses.

4.7. *Space-Based Science Opportunities*

The principal advantage of space-based astrometry is that we have diffraction-limited imaging all of the time, not only after employing extraordinary technologies such as adaptive optics or speckle interferometry. Diffraction-limited imaging means that we always have the photons concentrated within a few pixels and therefore reach faint limiting magnitudes in a short time and can determine very accurate image centers. Depending on the optical characteristics of the telescope, we can determine either the relative or absolute positions of the objects.

By taking advantage of the above characteristics, all of the projected space-astrometry projects, e.g. Gaia, JASMINE, SIM, OBSS can determine positions, parallaxes and proper motions for stars throughout major portions of our Galaxy. Most of the fundamental research problems can be tackled from the ground at some level, but often space astrometry is required to achieve definitive results. Ground-based astrometry will provide the general trends, e.g. the slope of the mass-luminosity relationship, but space astrometry is required to accurately measure the deviations from the relationship that can then be used in stellar evolution comparisons such as the change of helium with respect to metals as a star evolves. Other examples include definitive studies of the orbits of the globular clusters, local group members and of merging dwarf galaxies, an accurate determination of the rotation curve of the Galaxy and of its mass distribution and the definition of the distance scale within the local group.

Some research topics will be unique to space astrometry, such as the discovery and characterizing of Earth-mass extra-solar planets. Ground-based radial velocity surveys have been able to determine the general characteristics of the more massive extra-solar planets, but the details await astrometry, which can determine the inclination of the orbits and then the masses, not only the mass times the sine of the inclination. It is remarkable to note that all of the space-astrometry satellites will be able to determine the distance to the galactic center with an accuracy of 10% based on the observation of a single star, while today an average of all types of measures does not even achieve that accuracy! Likewise, the distances and luminosities of our galactic standard candles, the Cepheids and RR Lyrae stars will be determined once and for all, yielding a definitive distance scale within the local group and extending on to the nearby universe. Measurements of the subdwarf binary stars will give us the long-sought relationship between absolute magnitude, metallicity and mass.

4.8. *Challenges for Space Astrometry*

The principal challenge that I see for space astrometry is that the initial goals for Hipparcos and the HST were to achieve astrometric accuracy a factor of ten better than was then possible. All of the currently planned space astrometry projects are projecting a factor of 100 or more than Hipparcos and HST have been able to obtain. The extraordinary efforts of the Hipparcos and HST projects achieved a factor of 20 instead of their goal of 10. For Gaia, SIM, JAMSMINE and OBSS it will take an even greater effort by outstanding astrometrists to achieve their more optimistic goals.

5. CONCLUSIONS

I believe that the potential for astrometry to contribute to science is greater than at any time in history. A desperate need exists to train young scientists in astrometry to make the most of this exciting future. Unfortunately, there is a trend, especially in the United States for diminishing support for astrometry. We need to convince the funding agencies, universities, observatories and astronomical institutes to support the education of astrometrists, their research and to hire them into permanent positions.

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