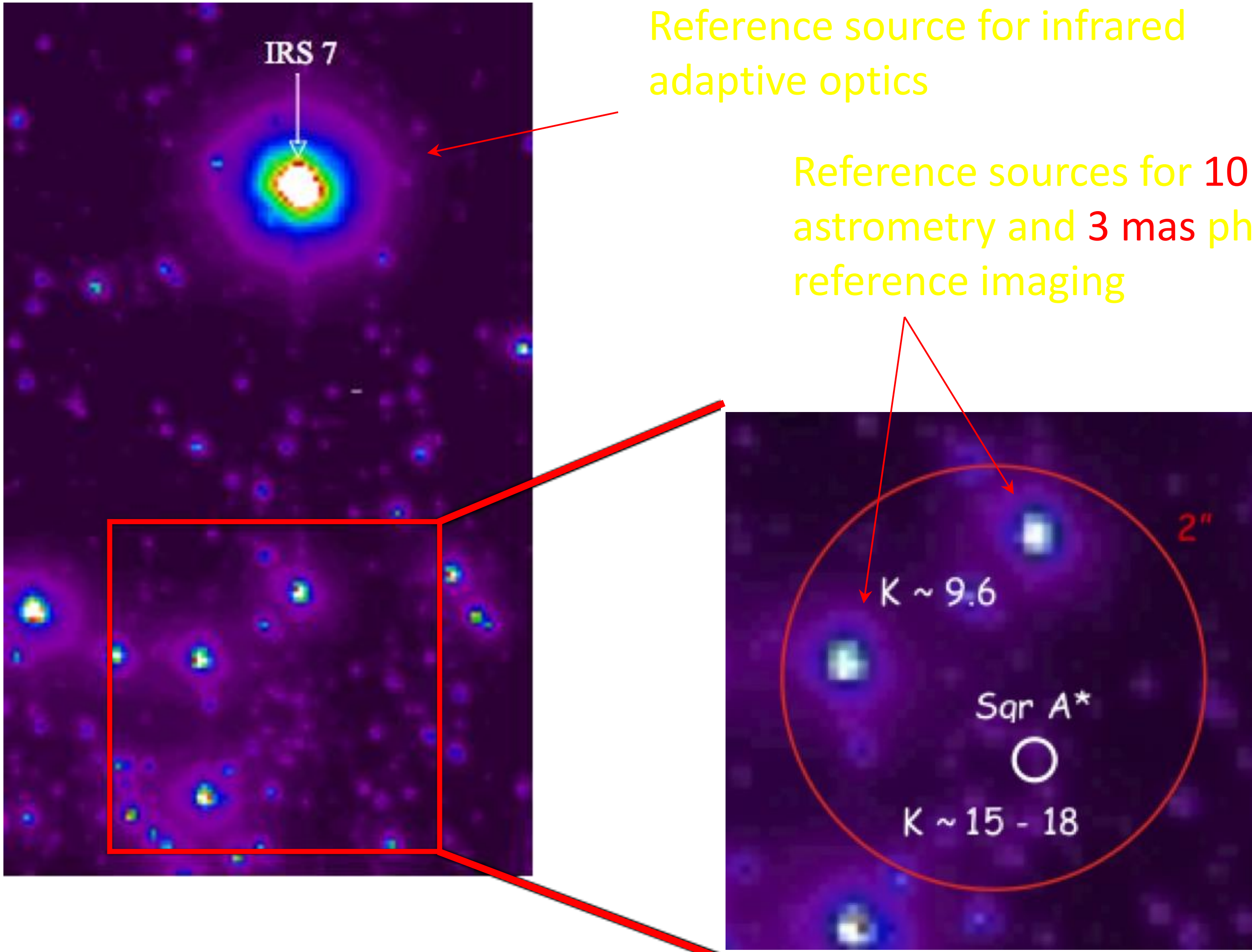
Principle of the measurements with GRAVITY



Improving Galactic Center Astrometry by Reducing the Effects of Geometric Distortion

S. Yelda[1], J. R. Lu[2], A. M. Ghez[1,3], W. Clarkson[4], J. Anderson[5], T. Do[6], K. Matthews[2]

ABSTRACT

We present significantly improved proper motion measurements of the Milky Way's central stellar cluster. These improvements are made possible by refining our astrometric reference frame with a new geometric optical distortion model for the W. M. Keck II 10 m telescope's Adaptive Optics camera (NIRC2) in its narrow field mode. For the first time, this distortion model is constructed from on-sky measurements, and is made available to the public in the form of FITS files. When applied to widely dithered images, it produces residuals in the separations of stars that are a factor of ∼3 smaller compared to the outcome using previous models. By applying this new model, along with corrections for differential atmospheric refraction, to widely dithered images of SiO masers at the Galactic center, we improve our ability to tie into the precisely measured radio Sgr A*-rest frame. The resulting infrared reference frame is ∼2-3 times more accurate and stable than earlier published efforts. In this reference frame, Sgr A* is localized to within a position of 0.6 mas and a velocity of 0.09 mas yr^{-1}, or ∼3.4 km s^{-1} at 8 kpc (1σ). Also, proper motions for members of the central stellar cluster are more accurate, although less precise, due to the limited number of these wide field measurements. These proper motion measurements show that, with respect to Sgr A*, the central stellar cluster has no rotation in the plane of the sky to within 0.3 mas yr^{-1} arcsec^{-1}, has no net translational motion with respect to Sgr A* to within 0.1 mas yr^{-1}, and has net rotation perpendicular to the plane of the sky along the Galactic plane, as has previously been observed. While earlier proper motion studies defined a reference frame by assuming no net motion of the stellar cluster, this approach is fundamentally limited by the cluster's intrinsic dispersion and therefore will not improve with time. We define a reference frame with SiO masers and this reference frame's stability should improve steadily with future measurements of the SiO masers in this region ($\propto t^{3/2}$). This is essential for achieving the necessary reference frame stability required to detect

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[1]UCLA Department of Physics and Astronomy, Los Angeles, CA 90095 -1547; syelda, ghez@astro.ucla.edu

[2]Astrophysics, California Institute of Technology, MC 249-17, Pasadena, CA 91125; jlu, kym@caltech.edu

[3]UCLA Institute of Geophysics and Planetary Physics, Los Angeles, CA 90095-1565

[4]Indiana University, Department of Astronomy, Bloomington, IN 47405; clarkson@astro.ucla.edu

[5]Space Telescope Science Institute, 3700 San Martin Drive, Baltimore, MD 21218; jayander@stsci.edu

[6]UC Irvine Department of Physics and Astronomy, Irvine, CA 92697; tdo@astro.ucla.edu

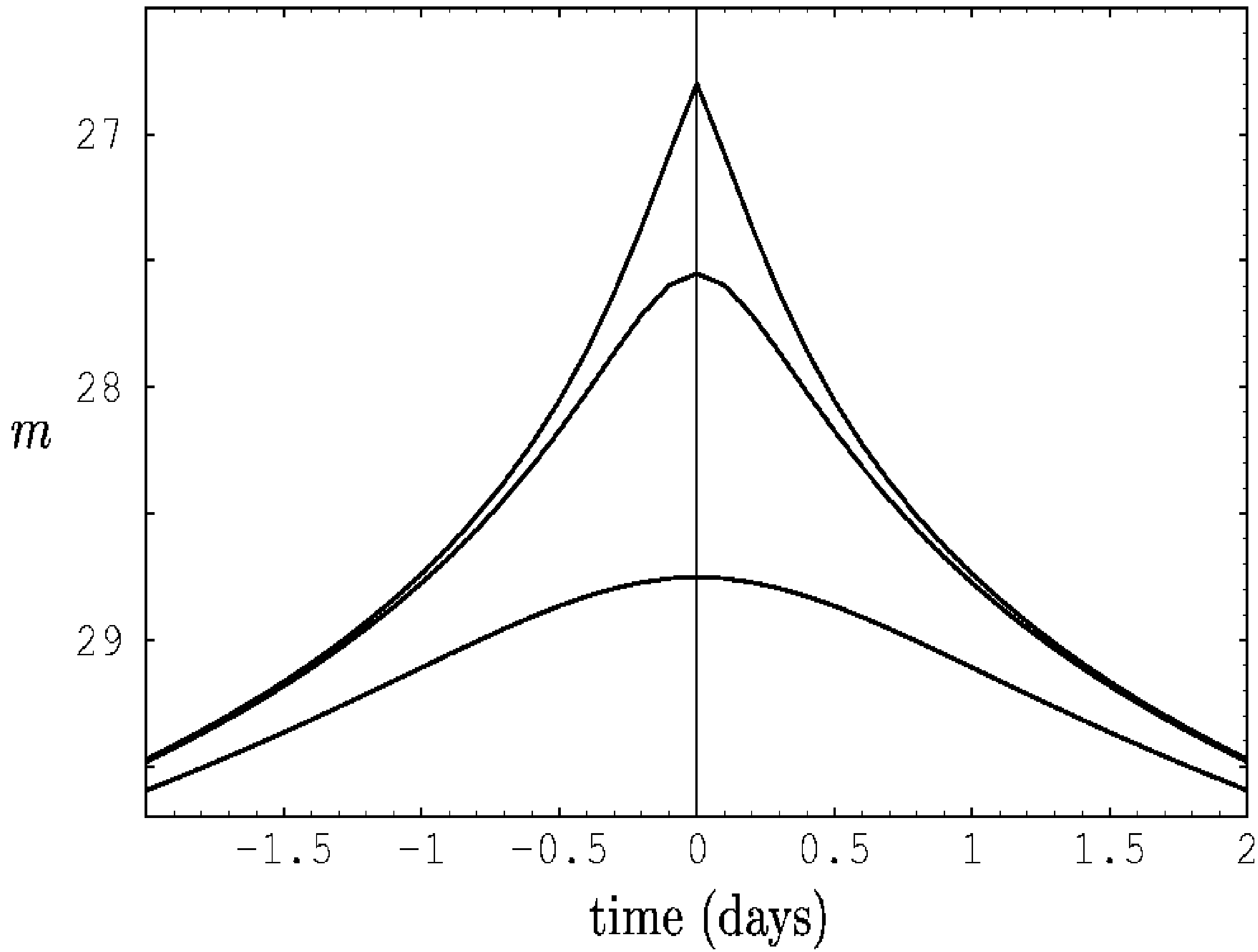

FIG. 3.— Solar retro-MACHO lightcurves: The apparent visual magnitude, m, of the Sun, imaged in a $10\,M_{\odot}$ black hole at a distance of 0.01 pc. The different curves are for the black hole at angular displacements from the ecliptic plane of 0, $R_{\odot}/1\,\mathrm{AU}$, and 1° respectively (top to bottom).

TABLE 1

RETRO-MACHO BRIGHTNESSES OF THE SUN

BH mass ($M_\odot$)	BH distance (pc)	$\beta = 0$ (perfect alignment)	$\beta = R_\odot/1\,\mathrm{AU}$ (edge alignment)	$\beta = 1^\circ$	$\beta = \pi/4$	$\beta = \pi/2$ (max misalignment)
1	10^{-2}	31.0	32.6	34	38	38
1	10^{-1}	38.6	40.1	41	45	46
10	10^{-2}	26.1	27.6	29	33	33
10	10^{-1}	33.6	35.1	36	40	41
10	1	41.1	42.6	44	48	48

Equations of motion

Kerr metric

$$ds^2 = -\frac{\Delta}{\rho^2}\left(dt - a\sin^2\theta d\phi\right)^2 + \frac{\rho^2}{\Delta}dr^2 + \rho^2 d\theta^2 +$$

$$+\frac{\sin^2\theta}{\rho^2}\left[\left(r^2 + a^2\right)d\phi - a dt\right]^2$$

or

$$ds^2 = -\left(1 - \frac{2Mr}{\rho^2}\right)dt^2 + \frac{\rho^2}{\Delta}dr^2 + \rho^2 d\theta^2 +$$

$$+\left(r^2 + a^2 + \frac{2Mra^2}{\rho^2}\sin^2\theta\right)\sin^2\theta\, d\phi^2 - \frac{4Mra}{\rho^2}\sin^2\theta\, d\phi dt,$$

- **Institute for Theoretical and Experimental Physics was founded on December 1, 1945. The heavy-water reactor was run in 1949, in 1961 the 7-GeV proton synchrotron started operating. It was the first Russian proton accelerator using the strong focusing principle. Besides, it was a small prototype of the biggest Russian 76-GeV machine built later in Protvino. Now ITEP is one of the most important scientific centers aimed at studying nuclear physics and physics of elementary particles. The Institute occupies the area of the old eighteenth century estate "Cheremushki".**
- **The founder was Academician A.I. Alikhanov**