Astronomy with Adaptive Optics on Moderate sized Telescopes

Hale telescope (200 inches)

P60 telescope (60 inches) ROBO-AO

Richard Dekany

Christoff Baranec

Keck 1 and 2 (10 m)

Roger Smith

Reed Riddle

IUCAA 08/23/11

Sergi R Hildebrandt, Caltech
Astronomy with Adaptive Optics on Moderate sized Telescopes

Tests of gravity via astrometry: 4 challenges for Robo-AO at IGO/IUCAA
Dark energy: its physical origin is unclear. $10^{39}\text{g/cm}^3$, $1.7 \times 10^{23}$ $M_\odot / \text{AU}^3$, $1.5 \times 10^7 M_\odot / \text{pc}^3$, where $M_\odot$ is the mass of the Sun. It adds $1.5 \times 10^5 M_\odot$ to the Milky Way ($10^7$) considering a volume of radius 10 kpc. Its effect is tiny in astrophysical terms. It belongs to cosmology.

- Dark matter: observational indications, but no direct detection of its constituents yet. Or, instead, one can modify the gravitational field equations: MOG\(^1\) (Modified Gravity) and MOND\(^2\) (MOdified Newtonian Dynamics).

4 challenges merging astrometry and gravity

With Robo-AO at IGO\(^(*)\), can we test ...

- Modified Newtonian gravity?
- Weak field limit of General relativity?
- The existence of intermediate mass black holes?
- The advance of the periapsis of stars around the galactic center?

There are other astrometry programs as the search and characterization of close binary star systems and their orbits, also useful to other missions, like Gaia in 2013, that I will not discuss here because they are viable.

\(^(*)\) Also at other Indian observatories: Himalayan Chandra Telescope, Devasthal Optical Telescope, ...
Testing Modified Newtonian gravity

- MOG: does not differ from Newtonian dynamics at the scales of galactic dynamics or weaker regimes, like, e.g., globular clusters. It is very difficult to test via astrometry.

- MOND: it departs from Newtonian dynamics whenever the acceleration of the particles is of order $10^{-10} \text{ m/s}^2$ with respect to some universal frame - it can be identified with the barycenter of the, ideally, isolated gravitational system in consideration. This conceptual ambiguity is solved with its covariant version: TeVeS$^3$.

- MOND has been applied to many scenarios as an alternative to dark matter with a high success. However, if MOND were ruled out, MOG would remain as the alternative to dark matter via modification of gravity.

- Which test is the weakest observational one of the MOND paradigm?

Globular clusters (GC) may have many stars ($10^4$ to $10^6$), are the oldest objects in the galaxy (10-12 Gyr) and have reached their relaxation times. The ones with more stars are located in the halo and most of them are farther than 7 kpc from the galactic center where MOND effects should not be affected by the local gravity of the galaxy.
Testing Modified Newtonian gravity

\[ v = 40 \text{ km/s} \times \frac{D_{\text{kpc}}}{N_{\text{hours}}} \]

For Robo-AO at IGO, for \( \gamma = 200 \) as, \( D = 7 \text{ kpc} \), \( v = 1 \text{ km/s} \), it means 6 years of open shutter... Impossible. Feasible for SPRITE or for larger telescopes and even so, it requires a great control of systematic effects.

4) Moffat and Toth 2008
Testing Modified Newtonian gravity

Thanks to multi-grid astrometry (CBK, 5), Robo-AO at IGO will achieve an astrometric precision as good (or better) than the one in the HST, despite the difference in wavelengths between the WFPC (0.55 m) and the K band.

• The HST observations date back already 11-15 years.

In fact, if the time span is 10 years with a 200 as precision at IGO, it is possible to measure via astrometry changes equivalent to 1 km/s and perform tests about MOND in halo GC.

• Quite a few of the GC extensively observed by HST are close to the zenith at IGO (M15, M13, M5, ...) in November out of the Monsoon season.

5) CBK: Cameron, Britton & Kulkarni (2009)
Testing Modified Newtonian gravity

Summary (i)

Tools:

* Geometrical field distortion of the chip: M5, M15, M13 close to the zenith in October-November.
* Grid astrometry: CBK paper.
* Analysis of HST observations (existing tools).

Results:

* Does MOND pass the test?
IGO is at a good location to observe orbiting solar objects. It is possible to fit the data to the derived post-Newtonian (PN) orbital motion. The latter can be derived by the aid of the JPL/Caltech ephemeris utility “Horizons system” (6). PN dynamics:

\[ \vec{v} = \frac{d\vec{x}}{dt} = \left( \frac{m}{p} \right)^{\frac{1}{2}} (-\sin \phi, e + \cos \phi, 0) + \vec{v}_{PN} \]

\[ v_{PN}^x = \sqrt{\frac{m^2}{p^2} \left[ -(2\gamma + 2 - \beta) e \phi' + (2\beta + \gamma - \nu) \sin \phi' - \left( \gamma + \frac{21}{8}\nu \right) e^2 \sin \phi' \\ + \frac{1}{2}(\beta - 2\nu) e \sin 2\phi' - \frac{5}{8}e^2 \sin 3\phi' \right]} \]

\[ v_{PN}^y = \sqrt{\frac{m^2}{p^2} \left[ -(2\beta + \gamma - \nu) \cos \phi' - \left( \gamma + 2 - \frac{31}{8}\nu \right) e^2 \cos \phi' \\ - \frac{1}{2}(\beta - 2\nu) e \cos 2\phi' + \frac{5}{8}e^2 \cos 3\phi' \right]} \]

\[ \delta \phi = \frac{6\pi G M}{a(1-e^2)c^2} \left[ \frac{(2-\beta+2\gamma)}{3} \right] + \frac{6\pi R^2}{2a(1-\epsilon^2)^2} \left[ 1 - \frac{3}{2}\sin^2 i \right] J_2 \]

There are quite a few asteroids close to the Earth's orbit, with orbital period of 1 year, $K$ between 14.5-17.5 and with high eccentricity $e>0.65$: 1999 KW4, 1999 MN, 2000 BD19, 2000 EE14, 2008 EA32, Icarus, Phaethon, Talos, ... The perihelion shift is between 100-250 as per year\textsuperscript{9}.

Therefore, Robo-AO observations could be compared with Horizons/JPL ephemeris and the beta PN parameter derived from astrometry.

It is also useful to evaluate the convenience of the multi-grid calibration of the geometrical distortion and scale of the chip given the high accuracy in Horizons/JPL ephemeris.

Although the precision in beta and gamma, after a year observing 7 objects in 5 convenient epochs may be low (10%), the same methodology would apply other telescopes.

The program can be extended to comets and constrain the influence of the pressure of the solar radiation in their orbital evolution.

9) J.L. Margot and J.D. Giorgini, 2009
Weak field limit of general relativity

Summary (ii)

Tools:
* Learning of Horizon ephemeris: prediction (there should be (see GC later)
* Check of stability of geometrical distortion in the chip when calibrating with a GC and observing a different (less crowded) field: multi-pointing, multi-grid astrometry: application of CBK to different pointing.

Results
* PPN beta from AO. The tests with other telescopes would follow this methodology.
* NEA and comets science. Close-up loop with Palomar observatory.
Intermediate Mass Black Holes

Black hole (BH) candidates of stellar mass (1-6 solar masses) have been detected in our galaxy through X-ray spectroscopy, Quasi periodic oscillations and ground infrared observations.

On the other side, there is a strong evidence for the existence of super massive BH (SMBH) of few millions of solar masses in the center of several galaxies. In the Milky Way case, it is around 4.5 millions of solar masses.

However, the evidence for BH with few hundreds or thousands of solar masses is considerably weaker. There is still a debate about the proposed candidates to intermediate mass BH (IMBH).

The best candidates are: M15 with an IMBH of 1000 $M_{\odot}$, Omega Centauris of 8000, G1 of , IRS13 of 1300.

(*) Credit: K.S. Thorne (Caltech)
Intermediate Mass Black Holes

Observations of globular clusters with a similar strategy as in the case of MOND, but studying their centers. One would infer curves of cusp velocity (recall the 1 km/s precision). Although it varies, M15 (10-15 km/s).

Learning the N-body simulations in clusters\(^9\).

Confusion attenuated by filtering techniques (50-100 as) in images as a post-processing ...

\(^9\) H. Z. Akram et al. (March 2011)
Intermediate Mass Black Holes

Figure 12. FASTCAM observations of the M15 core and corresponding wavelet filtering result. See text for details.

Much cheaper than NGAO (!) and may well be also useful for NGAO post-processing.

Check FastCam papers, where I was the project scientist before leaving to Caltech
Advance of periapsis around the GC

There are detailed studies that estimate the mass of the central super-massive black hole (SBH) in the Milky Way. Its mass is estimated in $4.5 \pm 0.4 \times 10^6 M_\odot$ (10).

The Galactic center is surrounded by a set of stars: the S Stars (10). Their mean dispersion velocity is very high: 400 km/s. There are some significantly faster. In particular S02 moves in its periapsis at a speed of 1% of light (again in 2018). S stars help deriving the mass of the central object and are also useful to conduct some tests on gravity (orbits, equivalence principle, BH horizon, Kerr metric).

10) A.Ghez et al. 2008
Advance of periapsis around the GC

The inclusion of the angular momentum of the SMBH and its determination is a subject presently of high interest and debate. However, its effect on the orbits is one order of magnitude lower than the one associated with the mass itself (Schwarzschild metric). Let's start with the purely mass effect. Taking into account the estimated mass of the SBH, one has:

\[
\theta = \frac{13.5 \text{ arcmin}}{(1-e^2)a}, \text{ per orbital period, where } e \text{ is the eccentricity of the star's orbit and } a \text{ is its semi-major axis in units of mpc.}
\]

Taking into account the distance to the GC, 8000 kpc, a precision of 100 as in the position of a S star corresponds to an opening angle in the reference system of the SMBH of

\[
\theta = \frac{13.3 \text{ arcmin}}{a}
\]

This is a remarkable coincidence. It makes it independent of the S star semi-major axis and compatible with Robo-AO at IGO.

However, the fact that the S stars have periods between 15-200 year sin addition to the confusion of the field in the innermost 500 mas, makes it really difficult. Perhaps a correlation technique with older images from Keck and a post-processing of the PSF halos, as in the case of the globular clusters, would make it possible.
All these goals and techniques for astrometry share direct interests with larger telescopes, in particular with present and upcoming projects at Keck (in particular, NIRC2) or Palomar (in particular, P3K, TMAS) - ask Richard Dekany.

And there are further synergies that may benefit other programs like the Palomar Transient Factory - ask Shri Kulkarni. See the PTF presentations on Wednesday.
Astronomy with Adaptive Optics on Moderate sized Telescopes

The proof: We are in Pune

THANK YOU VERY MUCH FOR THE ATTENTION & THE INVITATION!
2 J.W. Moffat, 2005, JCAP, 3
3 J.D. Bekenstein, 2004, PRD70, 083509