Astro2020 Science White Paper

Transverse Extragalactic Motions: a New Method for Constraining Cosmological Parameters

Thematic Areas: ☐ Planetary Systems ☐ Star and Planet Formation

☐Formation and Evolution of Compact Objects ☒ Cosmology and Fundamental Physics

☐Stars and Stellar Evolution ☐Resolved Stellar Populations and their Environments

☐Galaxy Evolution ☐Multi-Messenger Astronomy and Astrophysics

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Abstract: The current tension between the best-fit expansion rate H_o based on cosmological models from measurements of the cosmic expansion history (Type Ia supernovae (SN) and Baryon acoustic oscillations (BAO) combined with the CMB) and local measurements of H_o has reached the point where a consideration of non-standard cosmographic techniques seems prudent. The geometrical nature of strong lensing can provide an independent constraint, specifically through the modeling of multiple-arc systems where the details of a specific lens model may be minimized (e.g., Link & Pierce 1998; Julio et al. 2010; Magana et al. 2018). Furthermore, over the next decade, high resolution imaging via interferometers, such as ALMA, and the next generation of large ground-based telescopes will provide the capability to measure positions to unprecedented accuracy. This will permit a measure of the transverse co-moving distances for strongly lensed systems that result from our secular motion with respect to the CMB rest frame (this is the "Cosmological Parallax"). This measurement is interesting in that it is: independent of both SN and BAO, is geometrical, and the secular signal increases with time. A focused effort to model known multiple arc systems and to measure secular, cosmological parallaxes is proposed. Both show great promise for providing additional constraints on cosmological models.

Scientific Goals

1. Improving Cosmological Constraints from Gravitationally Lensing Systems with Multiple Sources

The present state of efforts to characterize the large-scale geometry of the universe has been recently summarized by Weinberg et al. (2013). Despite the enormous success of the SN and BAO constraints, there is tension between the inferred value of the Hubble parameter (H_o) and the local, empirical measurements of H_o (e.g., Reiss et al. 2016; Freedman 2017). This discrepancy, > 3σ, has now reached a sufficient level to cause some to suggest that alternative measurements of cosmography are needed.

The geometric nature of strong gravitational lensing can provide an independent constraint on cosmological models, particularly through the analysis of systems with multiple gravitational arcs, that is, those that are imaging multiple background sources at different redshifts. In this case, the degeneracy between the cosmology and the strength of the lensing potential can be broken (Link & Pierce 1998). The method has been successfully applied to several galaxy clusters having multiple arcs with measured redshifts and has produced interesting constraints on the angular-size redshift relation that is independent of BAO (Julio et al.2010; Magana et al. 2018). However, the models are currently limited by the need to model both the cluster potential and the potential from the individual galaxies within the cluster, some of which may not even be members but simply foreground or background galaxies projected onto the cluster population (Chirivi et al. 2018). In addition, any variations in the mass to light ratio of this population will result in systematic errors in the lens model that in turn limit the cosmological constraints for the system (i.e., the lensing potential, the

Figure 1: HST image of Abell 1689 with its numerous gravitational arcs from several background sources with differing redshifts (credit: NASA/APOD).

morphology of the background sources and the cosmology). A targeted effort to obtain internal velocity dispersions and spectral line indices (sensitive to age and metallicity) for the majority of the cluster population would require a substantial investment of telescope time on 8-meter class telescopes but the resulting data would provide significant constraints on the variations in the mass to light ratio of these perturbing systems. The result would be significantly improved models of these strong lensing systems and improved constraints for the cosmology. A directed effort to model more systems would result in improvements to the cosmological constraints. Just as importantly, improved modeling will improve magnification estimates for emission features the arcs from the current 10-30% accuracy (Meneghetti et al. 2017). LSST, WFIRST and EUCLID promise to discover rare, multiple-source lensing from individual galaxies. Their simplicity may provide the strongest cosmological constraints from multiple source lensing despite their rarity.

The Measurement of Transverse Extragalactic Motions: a New Technique for Constraining Cosmological Models

Various methods of measuring cosmological distances have been developed over the past decades (e.g., Weinberg 1971; Hogg 2000), including using the luminosity distance (SN) for locally calibrated standard candles and the angular-size redshift relation (BAO and lensing) to infer the distance. By contrast, astronomical parallaxes have traditionally been limited to only the nearest stars and have been dismissed as a cosmographic measure due to the effect occurring at the nano-arcsec scale for sources as cosmologically interesting distances. Nevertheless, cosmological parallaxes remain interesting because they are related to the "transverse co-moving distance" and are thus independent from the two traditional measures given above and the measurement of cosmological parallax may actually be feasible (Pierce 2019). Specifically, the parallactic distance (D_p) is:

$D_P = \mathrm{R}(t_0)\frac{D_M}{(1-kD_M^2)^{1/2}}$ where D_M is the transverse co-moving distance:

$$D_M(z) = \frac{D_H}{\sqrt{\Omega_K}} sinh\left[\sqrt{\Omega_K}\frac{D_c(z)}{D_H}\right] \quad \Omega_K > 0,$$
$$D_M(z) = D_c(z) \quad \Omega_K = 0$$
$$D_M(z) = \frac{D_H}{\sqrt{\Omega_K}} sin\left[\sqrt{\Omega_K}\frac{D_c(z)}{D_H}\right] \quad \Omega_K < 0$$

with $D_H = \frac{c}{H_0}$ and $D_C = \frac{c}{H_0}\int_0^z \frac{dz}{H(z)}$ (the line-of-sight co-moving distance) and with the Friedmann equation given by (Peebles 2000, Huterer & Turner 2003):

$\frac{H^2(z)}{H_0^2} = E(z)$ which for Dark Energy is:

$$E^2 = \Omega_M(1+z)^3 + \Omega_K(1+z)^2 + \Omega_x exp\left[3\int_0^z \big(1 + w(x) dln(1+x)\big)\right]$$

$E(z)$ can be evaluated for any values of the Dark Energy and cosmological parameters through numerical integration and the cosmological parallax vs redshift (due to Earth's motion around the sun) computed: 3×10^{-10} arcsec at z = 1 for the standard model. At first glance this appears so small as to make its measurement implausible. However, two factors exist that suggest that this might not be the full story. First: our 3-d space motion with respect to the CMB is actually 78 AU/year and is known to a few percent (Planck Collaboration 2018). Thus, over ten years the secular parallactic baseline grows to 780 AU. Second: strongly-lensed sources can have magnifications as high as 35, or even 50. Together, these result in a signal that is actually as much as 27,300 times larger than has been traditionally assumed bringing the secular parallactic signal for strongly lensed systems into the few micro-arcsec regime. *As a result, the measurement of cosmological parallaxes will soon become feasible!*

Over the next decade, the development of the next generation of large, ground-based telescopes with adaptive optics, will provide an imaging resolution of a few milli-arcsec. For example, one of the primary requirements of the first-light AO-assisted ELT instruments, such as IRIS on TMT, will be to provide milli-arcsec resolution with long-term astrometric precision of a few micro-arcsec, if a source contains complex structure and has a sufficiently high signal-to-noise. This is just what is required for the measurement of cosmological secular parallaxes. A sample of approximately 500-1000 strongly lensed galaxy-galaxy systems could be selected from lensed galaxy surveys via LSSST, WFIRST and Euclid. Within these systems, we are interested in finding those arcs that show small substructures very close to the critical line, where magnifications can exceed 50 (e.g. Vanzella et al. 2017). A down-selection of a subset of the best candidates would be undertaken after snapshot imaging via AO-assisted 8-meter class telescopes. IFU spectroscopy of the more promising systems would provide the redshifts of the lens and source in each system. These data are sufficient for baseline lens models of

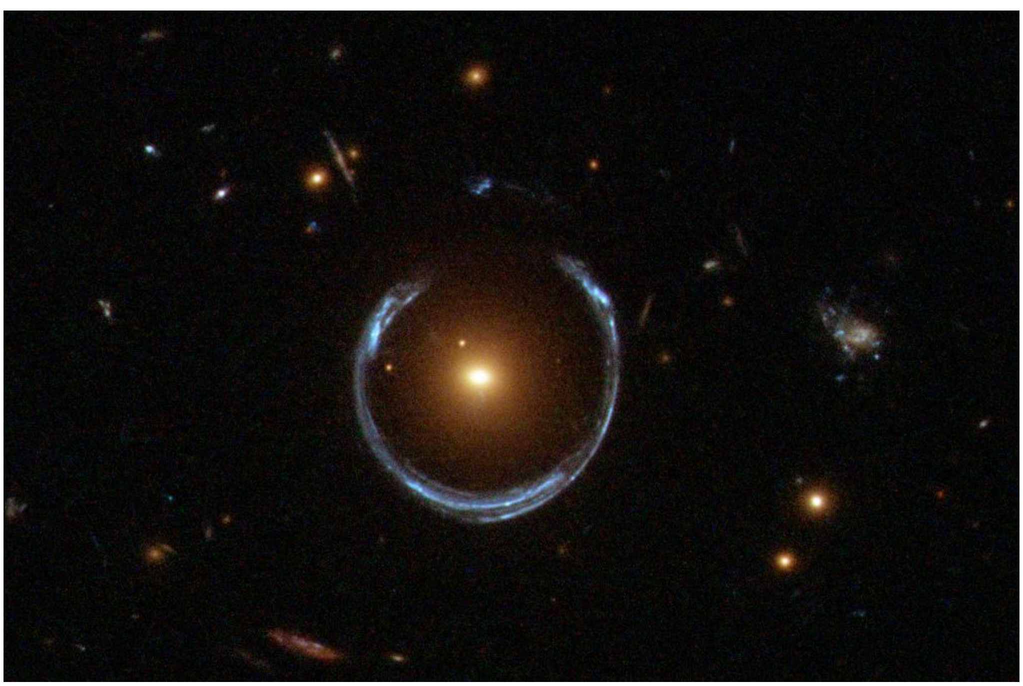

Figure 2: HST image of, the "Cosmic Horseshoe", nearly perfect Einstein Ring produced by galaxy-galaxy lensing (credit: NASA/APOD).

each system to be constructed in order to model source morphologies and determine the source positions relative to the critical curves of the lens so that the effect of the Galaxy's secular motion with respect to the CMB on the lensed sources could be predicted. The resulting "gold sample" would constitute the highest priority targets to be monitored over the next decade.

Figure 2 shows an HST image of SDSS J1148+1930, the "Cosmic Horseshoe" (Belokurov etal. 2007; Bellagamba, Tessore & Metcalf 2017), a galaxy-galaxy lens system that would be ideal for the measurement of cosmological parallaxes. Specifically, the lens (z ~ 0.5) is a dust-free, early type galaxy for which spectroscopy would yield a velocity dispersion and spectral line indices for baryonic mass-to-light ratios, the redshift of the source is high (~ 2.2) providing a large differential secular parallax signal, the source is also a blue, star forming galaxy. Its relatively high degree of structure thus makes it more sensitive to secular line-of-sight changes. There will be transverse motions of the lens and source as well but these will average out with a sufficiently large sample of systems leaving the secular parallax signal from the Galaxy's motion.

The ELTs will not come on line until the end of the next decade, so that the measurement of cosmological parallaxes using them, would still be in the future. However, the ALMA mm-wave interferometer can approach resolutions of a few milli-arcsec today. Furthermore, surveys of luminous, sub-mm sources have revealed a sample of strongly-lensed, high redshift sources (e.g., Negrello et al. 2010). An example of one of these sources, SDP.9 (Wong et al.2017) is shown in Figure 3. The large extent of the arcs is indicative of high

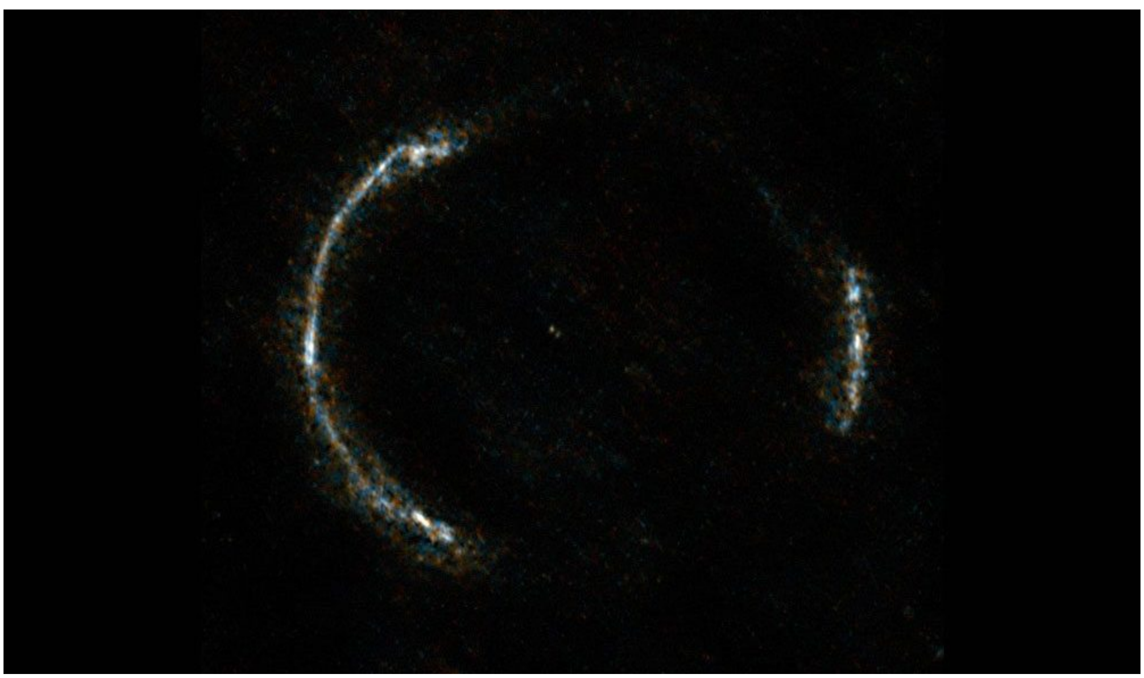

Figure 3: ALMA image of SDP.9 in CO (J = 6-5) showing the complex structure of the source. Continuum imaging can be matched to HST or JWST images to provide the location of the lensing galaxy relative to the background source (credit: NASA/APOD).

magnifications and the complex structure is ideal for the detection of small morphological changes as the source position appears to change with respect to the lens caustic due to the secular motion of the Galaxy. A targeted survey to identify suitable candidates would allow a sample of gravitationally lensed sub-mm sources to be identified and a down-selection similar to that described above to be undertaken. Monitoring of this sample could begin almost immediately allowing the proof of concept of the measurement of cosmological parallaxes. A measurement of the "effective cosmological parallax" may even be possible if a sufficiently large sample of these sources could be identified since the precision should increase with $\sqrt{N}$.

Summary

Gravitational lensing can provide powerful constraints on cosmological models that are independent of today's most popular methods (SN and BAO). Two approaches are advocated here:

1) the modeling of systems with multiple arcs has the potential to break the degeneracy between a particular cosmological model and the properties of the lensing cluster. This can provide an independent and purely geometrical constraint on the angular-size redshift relation, and thus the cosmography of the universe.

2) The motion of our Galaxy with respect to the CMB results in a secular, cosmological parallax that, when magnified via strong gravitational lensing, will be measurable for the first time in the coming decade. This is a consequence of the development of today's mm-wave interferometers, such as ALMA and the next generation of ELT's both of which are capable of milli-arcsec astrometric imaging. As the Galaxy moves through the universe the impact parameter of a lensed source changes, resulting in significant changes to the system morphology. Since our 3d motion is well known via the CMB dipole, the result is a predictable, systematic change to the system geometry. The measurement of these cosmological secular parallaxes will provide a new constraint on the geometry of the universe through the transverse co-moving distance, a new distance measure that is completely independent of those provided by SN and BAO. The potential of this new method is enormous, especially given that the cosmological "effective parallax" from all the systems continues to grow with time and should scale as $\sqrt{N}$, where *N* is the sample size.

References

Bellagamba, F., Tessore, N. & Metcalf, B. 2017, MNRAS, 464, 4823; Belokurov, V. et al. 2007, ApJL, 671, L9; Chirivi,G. et al. 2018, A&A, 614, A8; Freedman,W.L. 2017, arxiv.org/pdf/1706.02739; Hogg, D. W. 2000, arXiv:astro-ph/9905116v4; Huterer, D. & Turner, M. 2001, Phys. Rev. D 64, 123527; Julio, E. et al. 2010, Science, 329, 924; Kneib, J-P. & Natarajan, Pi. 2011, Astron. Astrophys. Rev., 19, 47; Link, R. & Pierce, M.J., 1998, ApJ, 502, 63; Magana, J. et al. 2018, ApJ, 865, 122; Meneghetti, M., et al., 2017, MNRAS, 472, 3177; Negrello,M. et al. 2010, Science, 330, 800; Pierce, M. J. 2019, in preparation; Peebles, P. J. E. 2000, Principles of Physical Cosmology, Princeton University Press, Princeton, pg. 310-321; Plank Collaboration 2018, arxiv:1807.06205; Reiss, A., et al., 2016, ApJ, 826, 26; Vanzella, E., et al., 2017, ApJ, 842, 47; Weinberg, D. 1971, Gravitation and Cosmology, John Wiley & Sons, New York, 418-427; Weinberg, D. H. et al. 2013, Physics Reports, 530, 87; Wong, K. C. et al. 2017, ApJL, 843, L35