

Astro2020 Science White Paper

Direct Acceleration: Cosmic and Exoplanet Synergies

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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Direct measurement of acceleration is a key scientific goal for both cosmology and exoplanets. For cosmology, the concept of redshift drift (more than 60 years old by the 2020s) could directly establish the Friedmann-Lemaître-Robertson-Walker model. It would increase the dark energy figure of merit by a factor of 3 beyond Stage 4 experiments, in combination with cosmic microwave background measurements. For exoplanets, the same technology required provides unprecedented radial velocity accuracy, enabling detection of Earth mass planets in the habitable zone. Other science cases include mapping the Milky Way gravitational potential and testing its dark matter distribution.

I. INTRODUCTION

Four frontier science areas can make great strides with the development of highly accurate and stable spectroscopy:

- Cosmic redshift drift and direct detection of cosmic acceleration;
- Earth mass exoplanet detection from radial velocities;
- Milky Way structure mapping through stellar accelerations;
- Dark matter properties through Milky Way gravity mapping.

Redshifts and Doppler velocities are central measurements for cosmology and for exoplanets respectively. While greater accuracy in exoplanet radial velocities is a recognized goal and major technology driver, in order to pick out Earth mass planets around distant stars, cosmological redshift precision has been sufficient for standard needs. However, the concept of redshift evolution over long timescales due to cosmic expansion – redshift drift – has repeatedly been brought up in the literature since it was first introduced by McVittie and Sandage in back to back articles in 1962 [1, 2].

Just as redshift is a direct measure of cosmic expansion, so redshift drift is a direct measure of cosmic acceleration. The characterization and identification of the origin of current cosmic acceleration is a major goal of cosmic surveys in the 2020s, such as the Large Synoptic Survey Telescope (LSST) and Dark Energy Spectroscopic Instrument (DESI). This cosmic acceleration is due to unknown new energy in the universe – a cosmological constant or dynamical dark energy – or to new laws of gravity beyond Einstein’s general relativity – or to a breakdown in the homogeneous and isotropic spacetime governed by the equation of the Friedmann-Lemaître-Robertson-Walker (FLRW) model. Direct measurement of cosmic acceleration can rule out the last possibility by confirming the reality of dynamical acceleration and give incisive new constraints on the properties of the effective dark energy, greatly complementary to those coming from the 2020s experiments under construction. Indeed it could increase their probative power by a factor three, turning them into Stage 5 experiments.

Redshift is due, in part, to the Doppler effect of the relative velocity between the source and observer. The change in “peculiar” velocity of a source induced by local forces thus represents a different contribution to redshift drift. While this motion might be considered as noise when determining the overall evolution of cosmic expansion, upon closer inspection

it is an interesting signal of the local gravitational forces caused by (dark) matter and is thus a probe of the mass distribution within the Milky Way, globular clusters, and galaxy clusters. Acceleration measurements of stars within the Milky Way map out the Galactic potential and explore the distribution and particle nature of dark matter [3, 4].

The technology path for high accuracy exoplanet radial velocity measurements is also eminently suited for cosmic acceleration observations [5]. Recognition of better astrophysical line sources – emission line galaxy surveys, particularly of OII doublets allowing differential rather than absolute measurements – a better window for dark energy characterization – at low redshift not high redshift – as well as new methods for canceling instrumental systematics, argues that the 2020s is the decade to use this synergy between cosmology and exoplanets to push development toward both science goals.

II. THE ACCURACY CHALLENGE

An Earth mass exoplanet orbiting a solar mass star in the habitable zone for life induces a radial velocity signal on the star of a few to ten cm/s. This is a Doppler shift of order $v/c \approx 10^{-10}$. The cosmological redshift of a source (say a galaxy emission line) changes by order one in a Hubble time, or approximately a factor $\Delta z \approx 10^{-10}$ in one year. These are extremely challenging levels, but their matching size reveals the synergy that exists in these science goals from common technology development.

In the cosmological case, we could build up measurements over a longer baseline, say of 10 years, or alternatively produce not just a detection, but a higher signal to noise characterization. So a 1% measurement over 10 years requires 10^{-11} accuracy. (We prefer 10^{-12} accuracy. Since one can improve by \sqrt{N} the precision using N sources, we will phrase this as 10^{-11} accuracy.) Large mass stars having Earth-like exoplanets further out have smaller Doppler shifts, so 10^{-11} accuracy benefits exoplanetary discovery and characterization science as well. Current Doppler radial velocity measurement precision has broken through the ~ 1 m/s level and is poised at 10^{-9} [6]. Concerted efforts for future improvement, and dedicated telescope time, could pay large scientific dividends for both cosmology and exoplanets search and characterization.

III. SCIENTIFIC OUTCOMES

Let us examine the prospective outcomes of acceleration measurements at the desired level. First for cosmology is simply the detection of the redshift drift. At high redshifts the Hubble time is shorter so the redshift drift is larger, though negative due to the matter dominated deceleration. This has led many to propose using sources at redshift $z > 2$. However, this does not account for the science goals – verification of the FLRW model within the accelerating epoch and characterization of the dark energy properties. The redshift drift $\dot{z} = dz/dt_0 = H_0(1+z) - H(z)$ peaks in acceleration around $z \approx 0.9$, achieving half its maximum height already by $z = 0.25$. Furthermore, at low redshift is the greatest discriminating power for dark energy.

Figure 1 shows the Dark Energy Task Force figure of merit on the dark energy equation of state parameters that distinguish between classes of cosmic acceleration: the present value w_0 and a measure of its time variation w_a . Low redshift measurements around $z = 0.3$, in combination with CMB data already existing, deliver a figure of merit of 1400. Note

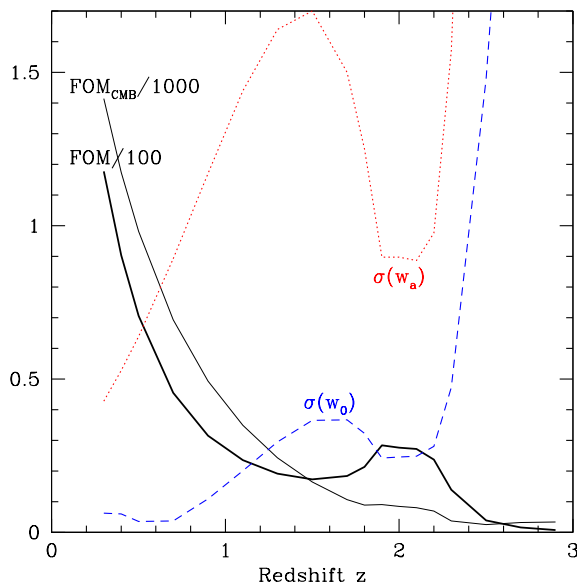


FIG. 1. Constraints at 1σ on dark energy w_0 and w_a , and their joint figure of merit (FOM), are plotted vs central redshift for experiments consisting of five measurements of redshift drift at 1% precision. CMB constraints are included in (only) the FOM_{CMB} curve; note it is shown divided by 1000 (i.e. the maximum is 1400), rather than 100 like the FOM curve without CMB.

this is independent of all other Stage 4 dark energy experiments such as LSST and DESI, offering not only a factor of 3 gain over them in isolation, and an independent crosscheck, but further gains from combination of all data together. Furthermore note that the emission line galaxies to be targeted are useful in themselves to the DESI and LSST surveys. Even diluting to a 5% redshift drift precision provides a roughly equal crosscheck to a Stage 4 experiment. Moreover, an improved measurement of the Hubble constant to 1.4% precision can increase the FOM to 2300, showing further synergy in 2020s science goals.

By contrast, surveys aiming at $z > 2$ are near pessimal. They are aiming at simple detection, but have little leverage on dark energy at such high redshift. This is the strategy followed by the CODEX spectrograph proposed for the European Extremely Large Telescope (EELT). By using many Lyman- α lines in quasar absorption spectra they hope to reduce the requirements on measurement precision. However, this drives them to very high resolution ($R > 120,000$) and a poor redshift range, as well as laying them open to astrophysical systematics from gas velocities and varying ionizing radiation field.

Thus the optimal low redshift range is ripe for US endeavors. Again, this is optimal not only for dark energy properties but in testing the FLRW framework against, e.g. void models or inhomogeneous universes such as Lemaître-Tolman-Bondi or Szekeres models that give the mirage of acceleration without true dynamics.

A further breakthrough involves the use of emission line surveys focusing on the forbidden OII doublet. While redshift (and redshift drift) affects the frequency of a line, it equally affects the spacing between lines. Thus we can turn an absolute measurement into a differential measurement of the spacing between well known doublet lines whose properties are determined by atomic physics. Emission line surveys using OII are standard workhorses of cosmology, used in the BOSS, eBOSS, and DESI surveys, and need only spectrographs of modest resolution $R \approx 5000$.

Galaxies have spatial structure with internal dynamics. Integral Field Unit (IFU) spectroscopy can provide spatial resolution, not only to distinguish between bulk and internal velocity evolution, but also to take advantage of the multiple spatially-resolved measurements of a line, each of which is narrower than the line when spatially-unresolved.

IV. SYSTEMATICS MITIGATION

The chief instrumental challenge is not spectral resolution, but wavelength stability: the point spread function (PSF) of conventional spectrographs drifts in position and shape under duress from thermal changes to the diffraction grating, fluctuations of air internal and external to spectrograph, a changing pupil, flexure of optical fibers etc. Conventional means for mitigating PSF drift include thermal control, vacuum tanks, adaptive optics, fiber optic scramblers, and laser frequency comb calibrants. These measures reduce the “insult”, $\delta\lambda_{\text{insult}}$, which reduces the error in the final spectrum. For purely dispersive spectrographs, $\delta\lambda_{\text{final}} = \delta\lambda_{\text{insult}}$, since the spatial scale of the detector is directly linked to the final spectrum, so requirements are severe on $\delta\lambda_{\text{insult}}$.

While such mitigations should be used if affordable, dispersive spectrograph stability can be further improved by 2 or 3 orders of magnitude by inclusion of a Michelson interferometer in series, as in externally dispersed interferometry (EDI). This technique has been used for precision Doppler radial velocimetry and high resolution spectroscopy [7–12] and discovered an exoplanet around star HD 102195 [13]. In this method the detailed wavelength determination is decoupled from the spatial scale in the disperser and its drift $\delta\lambda_{\text{insult}}$. Instead, the detailed wavelength is determined by the phase of a fringe (intensity measurement) in an interferometer cavity, which is calibrated by a spectral reference such as an iodine cell, ThAr lamp, or laser frequency comb. The cavity PSF is sinusoidal and has only three degrees of freedom (amplitude, period, phase). This is much easier to control or calibrate than the hundreds of degrees of freedom for a disperser PSF (at least one per grating groove).

Hence now the final PSF drift is given by $\delta\lambda_{\text{final}} = \delta\lambda_{\text{insult}} * TRC$, where TRC is the translation reaction coefficient of the spectroscopic method used. For dispersive spectroscopy $TRC = 1$; but for EDI using multiple delays we show (Sec. 10 of Ref. [11]) how to theoretically make $TRC = 0$. In recent demonstrations on a single ThAr line using the same data analysis software used in observations, we have obtained TRC as small as 1/1000! In our previous work we showed that the benefit of multiple delays, but without special weights, can achieve $TRC \sim 1/20$ [11]. In recent work however we used a technique called “crossfading” using strategically chosen weightings to force phase cancellation between a pair of delays, and have improved stability to $TRC \sim 1/1000$ (Fig. 2).

The crossfading technique works because under the same detector wavelength drift, EDI signals measured by a high delay will twist in one direction, and by a low delay will twist in the opposite direction. For final spectrum frequencies that lie in between a pair of (overlapping) delays, we choose weightings that cancel the net phase shift. We reweight (in software) for every pair of delays for each frequency, up to a limiting frequency of the highest delay. Crossfading also works with a single delay that overlaps the native PSF, and this stabilizes against drifts of all time scales. We have verified that crossfading also stabilizes against changes in PSF width or asymmetry.

In summary, the science cases can gain by significant instrumental systematics mitigation using crossfading EDI, because spatial drift of the disperser PSF is a dominant error source for current radial velocity spectrographs. Stability benefits multiply, so if using a fiber scrambler or vacuum tank provides, say, a 10^4 PSF drift reduction, then including the EDI could produce a $10^4 \times 1000 = 10^7$ net reduction.

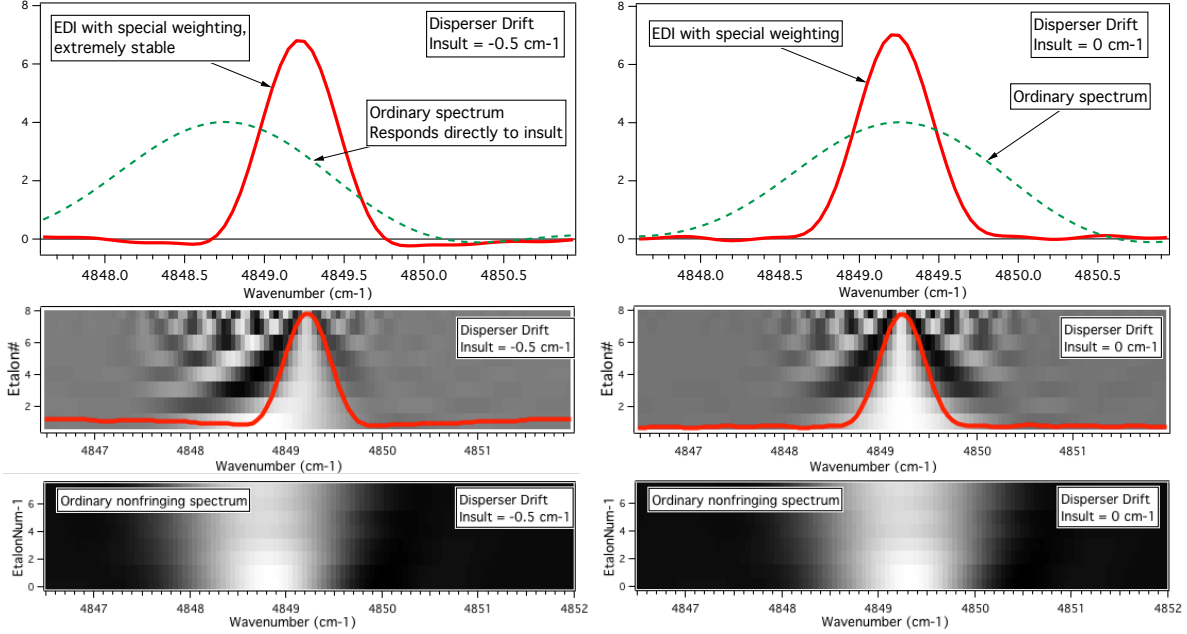


FIG. 2. A multiple delay externally dispersed interferometer boosts the stability and resolution of the disperser in series with it. Precision wavelength is obtained from the interferometric fringe phase, not the disperser, which mainly affects the fringe envelope (middle panels). Multiple delays (etalons) are used having different periodicities, which are summed to form the net EDI peak (red curve). Mount Palomar Observatory ThAr lamp line data [11] (right panels) is artificially shifted on the detector by 0.5 cm^{-1} (left panels). The disperser peak (green dashes) shifts directly, while the net EDI peak moves only $1/1000^{\text{th}}$ the amount.

V. CONCLUSION

Direct acceleration measurements are science goals of both cosmology, in the form of redshift drift, and exoplanet research, in high precision radial velocities to find Earth mass exoplanets, as well as Milky Way and dark matter mapping science cases. Support for technology advances in application of interferometric spectroscopy, and survey time, for these science goals can lead to revolutionary results. For cosmology, the use of differential measurements of forbidden OII doublet lines at low redshift is the optimal path, one not yet taken. Exposure time calculations indicate precision of a few times 10^{-9} can be achieved in 8 hours on a 10 meter telescope, for a single bright emission line galaxy at low redshift. Large numbers of objects will enable redshift drift measurements below the 10^{-10} level, with development of improved instrumental methods such as the already demonstrated delay shift technique. Astrophysical, “peculiar accelerations” will also be mapped by such surveys, revealing structure in the dark and dynamic universe, as well as our own Milky Way galaxy. The LIGO gravitational wave interferometer is a clear example of the advantages of using fringe phase shifts for making precision measurements for astrophysics.

The synergy of the enabling technology of high accuracy and stability spectroscopy for four astrophysics frontiers is truly extraordinary, and the 2020s is the decade when, with clear support, it can reach maturity.

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