Roman CCS White Paper

Setting the Stage for Improving the Distance Ladder with Roman Core Community Surveys

Roman Core Community Survey: *Choose from High Latitude Wide Area Survey, High Latitude Time Domain Survey, Galactic Bulge Time Domain Survey*

Scientific Categories: ***stellar populations and the interstellar medium****; also: stellar physics and stellar types; galaxies; large scale structure of the universe*

Additional scientific keywords: *Stellar distance; Evolved stars; Late-type stars; Stellar populations; Local Group; Variable stars*

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Abstract:

The upcoming Nancy Grace Roman (NGR) mission offers an unprecedented opportunity to improve the Cosmic Distance Ladder, and the Core Community Surveys (CCS) can play a key role in this endeavor. The use of long period variable stars (LPVs) as standard candles can extend our reach beyond the limits achievable with Cepheids, since the intrinsic luminosities of the LPVs are significantly higher and hence can be detected at larger distances. Recent work has calibrated the "J-AGB" method using J-band photometry and Gaia distances for Galactic carbon stars (Lee et al. 2021, 2022), and Hubble near-IR photometry of oxygen-rich Miras in supernova host galaxies (Huang et al. 2018, 2020). A significant limit of these methods to date, though, is the small number of galaxies to which they have been applied, largely due to limits of current facilities (fields-of-view, no/limited near-IR bands, sensitivity, insufficient revisit rate, etc.). Observations of nearby galaxies during the CCS on NGR could provide important data to address those limits.

Science Case - Background

A fundamental question in astrophysics is How far away is it? – regardless of what “it” is. The Cosmic Distance Ladder is built, step by step, by determining the distances to more nearby objects and working our way out. Knowing the distance to a star can help reveal its basic properties such as luminosity, mass, evolutionary state, and the distance to the system within which it resides. If that system is an external galaxy, knowing the distance to that galaxy can then improve our knowledge of cosmological parameter, particularly the Hubble constant, H_0. The current tension between different processes of determining H_0 shows how important it is to carefully crosscheck the results with independent methods, observing a wide variety of objects and mitigating any systematics that could impact the results.

Evolved stars, stars which have left the main sequence, have long been a part of the Cosmic Distance Ladder, particularly the variable stars. Henrietta Leavitt discovered the relationship between the periods (P∼a few to 10s of days) and luminosities of classic Cepheid variables in the Magellanic Clouds (Leavitt & Pickering 1912): if you know the period, you know the intrinsic luminosity, which then gives you the distance. This relation was used by Edwin Hubble, among others, to determine the distance to Andromeda and other Local Group galaxies (e.g., Hubble 1929). Asymptotic giant branch (AGB) stars are another type of variable post-main sequence star, in this case with periods of P∼100 to 3000 days. Those with periods up to P∼500 days have similar luminosities to the P∼10-day Cepheids in the near-infrared, but they are ***much more abundant*** than Cepheids as AGB progenitors can have a lower initial (main sequence) mass. The longer-period AGB stars are more luminous but less numerous and less well-behaved. AGB stars, especially those with P∼100-500 days, can potentially bridge the gap between the distances from the rarer extragalactic Cepheids and those from Type Ia supernovae (SNeIa). Thus, the AGB stellar populations potentially enable us to measure distances to SNeIa host galaxies that may not contain (useful) Cepheids. This could significantly improve the calibration of SNeIa luminosity by making full use of the SNeIa available in the volume where we can detect both stellar standard candles and SNeIa.

AGB stars are typically categorized by the dominant chemistry of the molecules and grains in their atmospheres and circumstellar envelopes. They will be either oxygen-rich M stars, with abundant oxides and silicates, or carbon-rich C stars with carbonaceous molecules and grains. In the Milky Way and galaxies with similar metallicities, M stars dominate the AGB population, whereas galaxies that are more metal-poor will have a larger fraction of carbon stars. Galaxies at larger redshifts tend to be lower metallicity than the Milky Way as fewer generations of stars have lived and died, and the products of their nucleosynthesis have had less time to be created and ejected to enrich the interstellar medium.

Recent efforts using near-infrared data from extragalactic AGB variables for each of these chemical types have increased our understanding of these stars and their properties, *particularly in better determining their distances*, and both new methods should have important roles to play in order to improve their utility as standard candles within the distance ladder.

The J-AGB method uses the location of the carbon stars in a near-infrared color-magnitude diagram (J vs. J-K). Madore & Freedman (2020) first explored this locus of carbon stars (the "J-region) as a distance indicator for the Large Magellanic Cloud. Lee et al. (2021) calibrated the method using *Gaia* distances to Galactic carbon stars, and Lee et al. (2022) demonstrated its accuracy to ~2% in M33.

For the oxygen-rich AGB stars, Huang et al. (2018, 2020) focused on the Mira variables, which are the most luminous, highest amplitude, and the most regular of the AGB variables. They used near-infrared photometry sparsely taken with *HST* over the course of ~1 year in a pilot set of SN Ia host galaxies to determine their distances. From these results primarily using H band data, they anticipate being able to determine H_0 from Miras to ~3%.

Both methods are very promising and should help resolve the tension between the current, discrepant estimates of H_0. However, they do need to be tested in and applied to more galaxies, with a wider range of properties such as metallicity, star formation activity, etc. – which is exactly where the NGR Core Community Surveys can play a key role.

Science Case – The Role of the NGR Core Community Surveys and Technical Requirements

The Core Community Surveys will use the Wide-Field Instrument on NGR. This instrument has a large field-of-view which can cover large portions, or even the entirety, of Local Group galaxies in a single pointing. It is also highly sensitive in the near-infrared and has a good angular resolution. These characteristics will make it an excellent instrument for resolving the stellar populations in nearby galaxies. With that kind of high-quality data, we can apply the J-AGB method to the carbon stars and find and characterize the O-rich AGB stars in each observed galaxy, determining its distance, and thus further testing the applicability of these methods.

Target regions: Every time a Local Group galaxy is within a survey region, even partially, a near-infrared color-magnitude diagram could potentially be generated from the resulting observations. Since the survey regions will be large, there will likely be numerous Local Group galaxies that will be observed. This is particularly true for the High Latitude Wide Area Survey.

For the other, smaller (as-yet notional) surveys, small changes in the nominal target region could be requested to better include a Local Group galaxy, although the field-of-view of the WFI is large enough that this might not be necessary. A preference would be for those galaxies that Boyer et al. (2015) observed in the mid-infrared with Spitzer, identifying hundreds of AGB stars which now need near-infrared photometry.

Filter selection: For the J-AGB method, two near-infrared filters are needed in order to create a color-magnitude diagram. The best filters for separating the carbon stars from the oxygen-rich stars and thus localizing the J-region in the color-magnitude diagram are J and K bands, roughly corresponding to NGR's F129 and F213. The O-rich Mira studies found H-band data worked well, or F158 on NGR; we do note that the *HST* WFC3 does not have a K-band filter, so it is quite possible that F213 would serve well instead for finding the Miras. Also, those *HST*-based studies noted that the O-rich Miras and carbon stars could be separated with their WFC3 filters, albeit not as well as with some other filter sets. Using F158 could potentially facilitate combining NGR data with archival *HST* observations. Thus, for this science case, J and K-equivalent bands are probably the best, but observations with J and either of H and K (or better yet, all 3!) would likely provide useful data.

Cadence: The oxygen-rich Miras with periods in the range of a few hundred days ($\sim$1 year) had the tightest P-L relation (i.e., the least scatter), and thus may be the best for distance determinations. Their study obtained 10-13 epochs, but even if only a small number of epochs (even one) were obtained with NGR, these could still be useful. More epochs are better, but any observations during the Core Community Survey program would help locate the AGB stars within the observed galaxies and would serve as pathfinders for follow-up studies, either with NGR itself or using other facilities.

Additional science utility: In addition to the potential for improving H_0 and the Cosmic Distance Ladder, these observations would contribute to other science areas. Other evolved objects such as red supergiants will also be located within the observed galaxies, and if multiple epochs are obtained, other variable stars and transient events will be found. AGB stars produce copious amounts of dust during this phase of stellar evolution, either carbonaceous or silicates, depending on the stellar chemistry, and play a vital role in the dust budget of galaxies. A good near-infrared census in Local Group galaxies will help better characterize this important stellar population for galaxy models and simulations, especially for comparisons with data at higher redshifts where the individual stars cannot be resolved. Evolved stars from $\sim$0.8 to 8 solar masses will also lose most of their mass while on the AGB, injecting significant amounts of material enriched with newly synthesized elements into the interstellar medium where it will be recycled into the next generation of stars and planets. Understanding their properties thus has implications from the fate of our own Sun to the evolution of galaxies and the Universe as a whole.

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