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4MOST Gaia RR Lyrae Survey (4GRoundS)

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The 4GRoundS survey will measure the radial velocities and metallicities of southern RR Lyrae stars in Gaia Data Release 3. These stars have excellent photometric distances, allowing the exquisite Gaia proper motions to be converted into physically useful transverse velocities. Armed with the missing radial velocity, 4GRoundS will provide the community with a dataset that will enable studies of the orbital structure of the halo and outer disc, and allow realistic modelling of these components. It will also enable the identification of coherent dynamically cold streams. Together these analyses will map the mass of the Milky Way out to 100 kpc and test models of the dark sector.

Scientific context

One of the main motivations for building the 4MOST spectrograph was to be able to undertake ground-breaking studies in Galactic archaeology, by using the kinematics and chemistry of the sub-populations of the Milky Way and its satellites as a means to test cosmology. The flurry of results emerging from analyses of Gaia data testifies to the great promise of this subject. Although Gaia has surveyed the astrometric sky to $G = 21$ mag, it is nevertheless highly limited in its ability to measure radial velocities (which will probably not probe beyond $G = 16–16.5$ mag even in the end-of-mission catalogue). Hence there is enormous scientific potential in complementing Gaia with radial velocities and spectroscopy from dedicated ground-based instruments. The 4MOST and WEAVE[1] instruments are in part a response to this clear need expressed by the astronomical community. The scientific goal of this endeavour is to flesh out the origins story of our Milky Way, explaining how it attained its present structure, and to attempt to verify whether its present phase-space configuration is consistent with the Lambda Cold Dark Matter (ΛCDM) cosmological framework that has been developed from the study of large-scale structure. But how can these goals be achieved observationally?

The required key observables are distance and velocity. It is natural to consider employing intrinsically bright stars that have stable atmospheres and narrow absorption lines, such as cool giants. Such stars will be among the most distant tracers that one can use to probe the Galaxy and its environment, and the resulting radial velocity measurements will be the most accurate. This consideration is almost certainly valid out to distances of approximately 10 kpc, where Gaia will provide good-accuracy (~ 10%) parallaxes to individual stars. For such stars the excellent Gaia proper motions can be converted to physically meaningful transverse velocities given the Gaia parallaxes. However, the Milky Way extends over a much larger volume, and indeed the region that is most dominated by dark matter (and is hence probably the most interesting for cosmology) lies in the outer halo, well beyond Gaia's ~ 10 kpc parallax horizon. The solution to this conundrum is for 4MOST to target stars for which alternative distance measurements are possible. The obvious options for tracer populations are Red Giant Branch (RGB) stars, Blue Horizontal Branch (BHB) stars and RR Lyrae stars.

RGB stars

As mentioned above, these yield excellent radial velocities, and their metallicities can be measured easily from spectra with low signal-to-noise (S/N). By assuming an age, the measured spectroscopic [Fe/H] allows one to place the star on a model isochrone and so estimate the star's distance given a measured photometric colour. However, the resulting distance uncertainties are large (~ 26%; Thomas et al., 2019), especially for metal-poor stars for which the RGB is nearly vertical in the colour-magnitude diagram. Furthermore, nearby dwarfs will contaminate the sample, which may be problematic at the faint end (which is a particularly interesting regime, since it probes RGBs at large distances) where Gaia parallaxes are uncertain and 4MOST spectra will have low S/N.

BHB stars

These Galactic tracers are also bright and have the desirable property of possessing a high contrast over other sources in the colour range that they cover. They can therefore be selected from photometry alone. Their hot atmospheres make it harder to measure accurate radial velocities, as absorption lines are much broader than in RGB stars. However, the main drawback of these tracers is that they cannot be easily differentiated from the intrinsically fainter blue straggler stars without good spectra. Furthermore, there is considerable spread in the absolute magnitude of BHB stars (Deason, Belokurov & Evans, 2011).

RR Lyrae stars

These variable stars possess several properties that make them essential tracers of the outer halo. First, they are easily identifiable from their photometric variability, including in the third Gaia data release (DR3) which has yielded an extremely clean all-sky sample (Clementini et al., 2022). Second, they are the best standard candles for old stellar populations, and are very well calibrated. Third, the RR Lyrae population exhibits a wide range of [Fe/H] (from above solar to at least as metal poor as –2.9 dex; Hansen et al., 2011), so they are a relatively unbiased tracer of ancient accretions. The main disadvantage of these stars is that their pulsations lead them to vary considerably in magnitude and in radial velocity, with amplitudes in the range from about 20–30 km s^{-1} up to about 80 km s^{-1} (depending on the pulsation mode). Part of this effect can, however, be corrected by modelling the velocity modulation with template velocity curves (Sesar, 2012) if the pulsation phase is known.

Specific scientific goals

The above considerations are the motivation for the 4MOST Gaia RR Lyrae Survey (4GRoundS), a community survey designed to measure the radial velocities and metallicities of as many RR Lyrae variables as possible over the southern sky. The input target list is the full Gaia DR3 sample (avoiding the Magellanic Clouds) which has state-of-the art astrometric solutions, photometry and full variability characterisation. Subsequent photometry and astrometry from the Legacy Survey of Space and Time (LSST) will complement the Gaia DR3 RR Lyrae sample, providing identification and type classification, distances, completeness and contamination information to the RR Lyrae population down to about 25.7 mag. We believe that the purity of this Gaia DR3 RR Lyrae sample, together with the excellent distance measurements, will enable several legacy studies of the dynamical properties of the stellar populations in the outer halo and distant disc using 4MOST. Given that the typical absolute magnitude of RR Lyrae is $M_G = 0.64$ mag. at [Fe/H] = –1.5 dex (Muraveva et al., 2018), the limiting magnitude of the Gaia RR Lyrae catalogue of $G = 20.7$ means that we reach a distance horizon of 100 kpc. The scientific applications of this dataset are extremely rich, as the sample will provide a unique six-dimensional view of the outer regions of the Milky Way. While we foresee numerous studies that will be undertaken with the survey data, here we briefly outline some particularly exciting sub-projects.

Dynamical mass modelling of the outer Galaxy

Supplied with radial velocities and distances, it will be possible to constrain the mass profile of the outer Galaxy, correcting for the measured orbital anisotropy as a function of radius, extending the analysis of Wegg, Gerhard & Bieth (2019). Such approaches based on the Jeans equation or relying on distribution function models (for example, Posti & Helmi, 2019), make the basic assumption that the Galaxy is an equilibrium structure. It will be fascinating to explore how the flattening of the dark matter distribution continues at large distance, and in particular whether the spherical halo shape deduced to ~ 20 kpc persists further out. Such behaviour is expected in some theories of gravity where the baryons source gravity (for example, MOND).

Stellar streams in the outer Galaxy

Gaia has identified many stellar streams in the inner Galaxy (Ibata et al., 2021). These structures are also very promising as probes of the acceleration field, and have the added advantage that they do not require the halo to be in equilibrium. By identifying even as few as three RR Lyrae with 4MOST that form a coherent grouping in action space, it will be possible to search around such candidate structures for other stars observed by 4MOST (for example as part of Consortium Survey 1) or for Gaia stars with similar stellar populations (or in deeper surveys such as LSST) to confirm the detection. The 4MOST and Gaia kinematics would yield the orbital properties of the streams. The comparison of the acceleration field measured with streams and that measured with the halo field population promises to reveal the extent to which the halo is out of equilibrium.

Search for low-mass satellites

In similar fashion, very small groupings of as few as two RR Lyrae stars with the same 4MOST radial velocity (and Gaia astrometry) may reveal the locations of the least luminous satellite galaxies (confirmable with LSST), probing the lowest mass limits of galaxy formation (for example, Sesar et al., 2014; Stringer et al., 2021; Petersen & Penarrubia, 2021). According to LCDM, these dwarf galaxies are the building blocks of the Milky Way and are expected to host an old and metal-poor stellar population. Although the intrinsic frequency of RR Lyrae is relatively small for an old and metal-poor stellar population, the contamination from any hypothetical smooth component sharply decreases with Galactocentric distance, so that overdensities of a few (~ 10 degree^{-2}) RR Lyrae are statistically significant. Also in this case, candidate dwarf galaxies can be verified with LSST or with dedicated photometric follow up.

Global halo kinematic asymmetry due to the arrival of the Large Magellanic Cloud

Recent models of the evolution of the Local Group suggest that the Large Magellanic Cloud (LMC) formed within an extremely massive halo, which is now just arriving into the Milky Way for the first time. The LMC's mass is large enough to produce a substantial asymmetry in the Milky Way's stellar halo (Garavito-Camargo et al., 2019), which should be detectable given tracers with good distance estimates. This study requires a differential measurement between the northern and southern hemispheres, which is possible as WEAVE will also target Gaia-selected RR Lyrae.

Distant disc

With their low contamination and excellent distances, the RR Lyrae will be wonderful probes of the dynamics of the far side of the (thick) disc, allowing us to study the global response of the disc to the arrival of the LMC and the repeated collisions with the Sagittarius dwarf (Laporte et al., 2018). Iorio & Belokurov (2021) have shown that there appear to be RR Lyrae with dynamical properties consistent with being thin-disc stars. These will be very useful for tracing the early build-up of the thin disc, in particular with the additional metallicity information.

Bulge/inner halo

The RR Lyrae in the inner few kpc of the Milky Way are an extremely old stellar population (13.41 ± 0.54 Gyr; Savino et al., 2020). They form a bulge spheroid, the nature of which is still unclear — it might be a small classical bulge, the result of a puffed up disc, or it could be the inner region of the halo (or a combination of these). Using the largest sample of RR Lyrae with radial velocities in the inner Galaxy to date (2768 stars), Kunder et al. (2020) find some evidence for different spatial and kinematic populations of RR Lyrae in the inner Galaxy. With a sample of inner-Galaxy RR Lyrae that is more than an order of magnitude larger than currently available (~ 50 000 in the bulge region), 4GRoundS will be able to accurately disentangle the halo and spheroidal bulge for the oldest populations in the inner galaxy, constraining the early formation of the Milky Way. This will provide a complementary perspective to that of 4MOST Consortium Survey 3.

Spatial variations in kinematic coherence through the halo

ΛCDM posits that all galaxies are constituted of a myriad of dark sub-halos. There is the hope of detecting these invisible sub-halos via their heating effect on star streams. Here we propose an alternative means to detect these dark matter substructures. Our simulations show that dark sub-halos with masses of $10^9\ M_{\odot}$ cause large convergent velocity flows of ~ 15 km s^{-1} in the stellar halo on scales out to ~ 2 kpc. To detect this signal, it is necessary to have good distance measurements, in order to pick out the populations at the distance of interest (and so suppress contamination from stars at different distances). Again, the excellent RR Lyrae distances are essential, and their 4MOST radial velocities, together with Gaia proper motions, will provide the velocity signal of interest. With this, we aim to construct a three-dimensional map of the velocity coherence (its local convergence and divergence) throughout the halo, and compare this result to numerical simulations in ΛCDM and with other prescriptions for gravity/dark matter. This will allow 4GRoundS to quantify the degree of lumpiness of the halo in the full 6D phase space. We will make use of robust estimators like, for example, the two-point correlation function calculated in this extended space and compare them with the same quantities measured in cosmological simulations and in smooth models of the halo to probe the validity of the currently favoured cosmological paradigm.

Target selection and survey area

The 4GRoundS input catalogue is simply the full Gaia DR3 sample of 271 779 RR Lyrae (Clementini et al., 2022), without any apparent magnitude cut, from which we aim to select targets as uniformly as possible over the full sky accessible to 4MOST. Assuming approximately 50% completeness in targeting, up to 100 000 RR Lyrae stars may be observed.

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References

Clementini, G. et al. 2022, arXiv:2206.06278
Deason, A., Belokurov, V. & Evans, N. W. 2011, MNRAS, 416, 2903
Garavito-Camargo, N. et al. 2019, ApJ, 884, 51
Hansen, C. J. et al. 2011, A&A, 527, A65
Ibata, R. et al. 2021, ApJ, 914, 123
Iorio, G. & Belokurov, V. 2021, MNRAS, 502, 5686
Kunder, A. et al. 2020, AJ, 159, 270
Laporte, C. F. P. et al. 2018, MNRAS, 481, 286
Muraveva, T. et al. 2018, MNRAS, 481, 1195
Petersen, M. S. & Peñarrubia, J. 2021, Nature Astronomy, 5, 251
Posti, L. & Helmi, A. 2019, A&A, 621, A56
Savino, A. et al. 2020, A&A, 641, 96
Sesar, B. 2012, AJ, 144, 114
Sesar, B. et al. 2014, ApJ, 793, 135
Stringer, K. M. et al. 2021, ApJ, 911, 109
Thomas, G. F. et al. 2019, ApJ, 886, 10
Wegg, C., Gerhard, O. & Bieth, M. 2019, MNRAS, 485, 3296

Links

[1] WEAVE instrument overview: https://www.ing.iac.es/astronomy/instruments/weave/weaveinst.html

This picture shows a new view of NGC 3603 (left) and NGC 3576 (right), two stunning nebulae imaged with ESO's Visible and Infrared Survey Telescope for Astronomy (VISTA). This infrared image peers through the dust in these nebulae, revealing details hidden in optical images.