FUTURE SPACE ASTROMETRY

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ABSTRACT. With Gaia's second data release in April of 2018 Europe entered a new era of space astrometry. Further data releases are also planned for the coming years. Despite this great progressastronomers are already looking towards the future. Gaia had an advantage over pointed missionsin being a global survey which provided absolute parallaxes and addressed a very broad range ofscience cases. However, Gaia only operates at optical wavelengths while much of the Galacticcentre and the spiral arm regions are obscured by interstellar extinction. One clear option for spaceastrometry is to shift to the infra-red where new science cases immediately become apparent. Thiscan, of course, be achieved with a pointed mission performing relative astrometry, such as theJapanese small-Jasmine concept, focused on the Galactic plane. However, I would argue that muchmore can be achieved by essentially replicating an all-sky Gaia-like mission with Near-InfraRed (NIR)detectors.

1. THE SCIENTIFIC MOTIVATION

The second Gaia data release contained astrometric data for ∼1.7 billion sources with tens of microarcsec (or microarcsec per year) accuracy in a vast volume of the Milky Way and future data releases will further improve on this. Gaia has just completed its nominal 5 year mission (July 2019), but is expected to continue operations for an extended period of an additional 5 years through to mid 2024. Its final catalogue to be released ∼2027 will provide astrometry for ∼2 billion sources, with astrometric precisions reaching 10 microarcsec.

In our recent white paper to the European Space Agencys (ESA's) Voyage2050 call we have outlined the detailed science cases for a new all-sky visible and NIR astrometry mission (Hobbs *et al.*, 2019a). With a wavelength cutoff in the K-band the new mission is not just focused on a single or small number of key science cases. Instead, it is extremely broad, answering key science questions in nearly every branch of astronomy while also providing a dense and accurate visible-NIR reference frame needed for future astronomy facilities. Such a new mission will require new types of detectors to scan the entire sky and measure global absoluteparallaxes. The spacecraft must have a constant rotation to scan the sky which results in a moving image that must becompensated for by, for example, operating the detectors in Time Delayed Integration (TDI) mode.

For around 2 billion common stars the combination of two all-sky space observatories would provide an astrometric foundation for all branches of astronomy – from the solar system and stellar systems, including exoplanet systems, to compact galaxies, quasars, neutron stars, binaries and dark matter (DM) substructures. The addition of NIR will result in up to 8 billion newly measured stars in some of the most obscured parts of our Galaxy, and crucially reveal the very heart of the Galactic bulge region (see Figure **??**).

In this paper I argue that rather than improving on the accuracy to answer specific science questions, a greater overall science return can be achieved by going deeper than Gaia and by expanding the wavelength range to the NIR. A new mission could expand and improve on the science cases of Gaia using basic astrometry. Key topics are focused on what dark matter is and how is it distributed, how the Milky Way was formed and how has it been impacted by mergers and collisions? How do stars form and how does stellar feedback affect star formation; what are

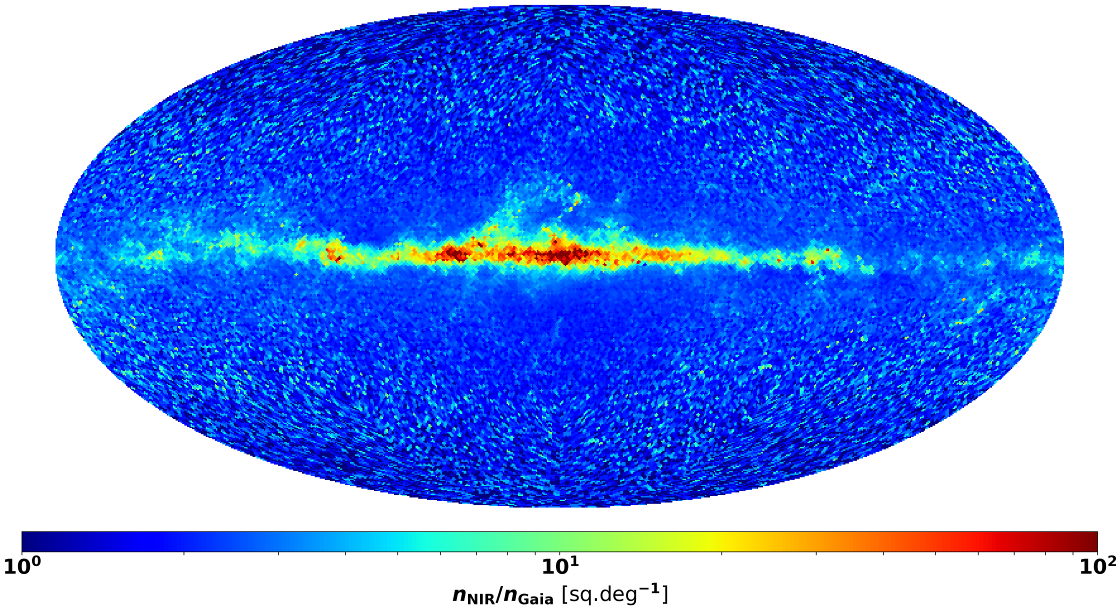

Figure 1: *All-sky projection in Galactic coordinates of the star count ratio per square degree between GaiaNIR and Gaia (G-band limit of 20.7th mag giving 1.5 billion Gaia sources). In total 5 times more stars could be observed, especially in the disk where extinction is highest, by GaiaNIR for the H-band limit of 20th mag (left figure) and 6 times more stars could be observed by including the K-band limit of 20th mag. Crowding is not taken into account here and will limit the increase in numbers in the densest areas. From Hobbs et al., 2019a.*

the properties of stars, particularly those shrouded in dust, and small solar system bodies; how are they distributed and what is their motion? How many co-planar systems like ours (with Earth-sized and giant planets) are there and what fraction have planets with long period orbits? To answer these questions there are three main science challenges for a new all-sky astrometry mission (The following is a brief summary of the discussion in Hobbs *et al.*, 2019a where more detailed arguments are given):

1.1 NIR astrometric science cases

NIR astrometry (and simultaneous photometry) is crucial for penetrating obscured regions and for observing intrinsically red objects when implemented with sufficient accuracy. Peering through the dust of the Milky Way to obtain a dense sampling of the phase space necessary to study the bulge, bar, bar-disk interface and spiral arms. Spiral structure can excite stars to radially migrate and induce disk heating and accurate measurements of the 3-D motion and properties of these obscured stars are needed to trace the dynamical history and evolution of our Galaxy. Preliminary estimates show that a new NIR astrometry mission would observe at least 5 times as many stars as Gaia, assuming the same magnitude range, giving a huge increase in the catalogue size and would dramatically increased phase space sampling of the disk, especially of the innermost regions where co-existing populations require better statistics.

Since Gaia was proposed, it has become clear that the evolution of the Milky Way is far more complex than had been realized. Not only is it not in equilibrium, its stars actually move away from their birth places, a process called radial migration which can vary with time and distance from the Galactic centre. Stars can be strongly influenced by the bulge and bar regions and their interaction with spiral arms and also by minor mergers. All of this implies that the local volume near the Sun cannot be understood in isolation, without a proper description of the innermost regions of the Milky Way and its merger history. A new NIR astrometry mission would allow us to probe this vast region and accurately determine the dynamics of the stars there.

The Milky Way presents our best opportunity to study the nature of dark matter, the gravitational force at different points in the inner disk of the Milky Way is not well known and many sources will not have been observed by Gaia so a new NIR mission would give unique measurements with similar accuracy to Gaia. The parallaxes, and proper motions at the Galactic centre distances will thus not be very accurate for many new sources. However, double epoch observations for bright stars will give a smaller sample of very accurate parallaxes and proper motions. The very unique all-sky astrometry that a new NIR mission can offer constrains the detailed dynamical and orbital structure of many more stars and at greater distances around the central black hole region than other surveys such as GRAVITY and Small-JASMINE.

Gaia has already shown that the Galactic plane itself shows clear signs of a warp and this means that conceptions of our Galaxy having a simple rotation curve which is a function of radius must be discarded, and we must map the velocity field across the Galactic plane. A future astrometric mission will allow us to do this far more accurately than Gaia alone, because of the improved proper motions, and working in the NIR will alleviate the selection effects caused by dust extinction revealing the stars in the midplane of the Galaxy that are not seen by Gaia.

Stars are continuously formed in clusters of tens to thousands and evolve together for a shorter ($\sim$ 100 Myr) or longer time (a few Gyr) in associations or open clusters, respectively, depending on whether they are gravitationally bound or unbound. Clusters are often located in the spiral arms of the Milky Way and are composed of young stars that have recently formed in the disk. The stars belonging to a cluster have roughly the same age and metallicity and can be used to probe the Galactic disk structure and formation rate, to study young star properties and their formation process as well as probing radial migration.

The spiral structure of the Milky Way is surprisingly poorly known, radio measurements are providing good constraints on the fundamental parameters of the Galaxy, including the distance to the Galactic centre, but are very limited in number. Spiral arms are also the main areas of star formation in the Milky Way, and are responsible for a significant portion of radial migration and disk heating. A new NIR astrometry mission can provide many more samples of stars in the disk plane with enough astrometric accuracy up to about the distance of 8 kpc, and can uncover the stellar motion around the Outer, Perseus, Local, Sagittarius, and Scutum-Centauras arms over a large range of Galactocentric radii and azimuthal angles. This will provide an ultimate answer for the origin of the spiral arms and will be key to resolving questions regarding the nature of dark matter, by showing us whether the Galaxy has a cored or cusped dark matter halo, whether there are any thin, disc-like components to the dark matter distribution, and whether spiral arms have their own dark matter component.

1.2 Improved proper motion science cases

A new mission could be combined with the older Gaia catalogue (currently $\sim$1.7 billion sources) with a 20 year interval to give a much longer baseline of 25–35 years, with very accurate proper motions (a factor of 14–20 better in the two components) and improved parallaxes needed to measure larger distances. While Gaia is making much progress it will not be sufficient to discover and characterise most of the stream-like structures in the halo. Improvements in the accuracy of proper motions would allow a new mission to resolve tangential motions in streams and local dwarf galaxies, with a potential accuracy of 2–3 $\mathrm{km\,s^{-1}}$ for specific samples out to $\sim$ 100 kpc. Additionally, improved proper motions will also be crucial to help disentangle the mixed populations in the bulge region. This is only possible by exploiting the long time baseline allowed by combining Gaia measurements with those from a future astrometric mission. This will provide great insight into the gravitational potential in the outer reaches of the Milky Way where halo streams are sensitive probes.

Streams in the Milky Way halo are formed when satellite galaxies or globular clusters are pulled apart in the tidal potential of the Milky Way. The stars then drift apart because they are on different orbits and form a (typically thin) band of stars across the sky. Improving proper motion measurements for stars in Milky Way streams will allow "gaps" in the streams to be identified more easily, we might see the influence of dark matter sub-haloes in the Milky Way's halo even though they contain no stellar matter. All this will allow us to determine the dark matter distribution at large radii, including any flattening of the potential, and the total mass of the Galaxy. A future astrometry mission would provide highly accurate proper motions and more accurate distances to these stars, which will allow much more precise determination of the potential of the Milky Way at these large radii.

A full understanding of the internal dynamics of dwarf spheroid galaxies still remains beyond our reach. There is a trade-off between dark matter content and tangential anisotropy and/or repeated tidal heating by encounters with the Milky Way which can masquerade as a highly dark matter dominated galaxy. The only way to be sure of the true dark matter content is to measure the internal proper motions of the stars in the dwarf galaxy, not only the bulk proper motion of the system (feasible with Gaia). Only the combination of Gaia and GaiaNIR can hope to achieve this challenging goal.

Astrometrically resolving internal dynamics of nearby galaxies, such as M31, dwarf spheroidal galaxies, globular clusters, the Large and Small Magellanic Clouds (LMC, SMC), sets requirements on the accuracy. For example, the LMC has a parallax of 20 μas and an accuracy of about 10% is needed, which is just within the reach of Gaia. Precise mapping of dark matter (sub-) structure in the local group (for instance Cen-A) and beyond is possible with accurate proper motions. Gaia can only just directly measure internal motions of nearby galaxies. Combining proper motions from two Gaia-like missions opens up the tantalising possibility of accurately measuring their internal motions and thus resolving the dynamics within the Local Group.

Proper motions and parallaxes, especially of binaries, will be much improved when astrometric data from two missions are combined and the detection of planets with significantly longer periods than by Gaia alone can be achieved. A significant population of stars with planetary system architectures similar to our Sun's (so long period, massive gas giants, like Jupiter and Saturn, in the outer reaches, shielding Earth type planets in the star's habitable zone) will be discovered. Another strong impact is on the study of the population of small Solar System bodies, asteroids, comets, and planetary satellites. Solar System bodies are easily perturbed and repeated high accuracy astrometry and photometry are needed improve our knowledge here.

1.3 Maintenance of the celestial reference frame

A new mission would allow the slowly degrading accuracy of the Gaia visible reference frame, which will become the fundamental Celestial Reference Frame (CRF) and the basis for all modern astronomical measurements, to be re-initialised back to a maximal precision. This degradation is due to errors in its spin and due to small proper motion patterns which are not accounted for. The catalogue accuracy itself will decay more rapidly due to errors in the measured proper motions. However, the million or so quasars expected in the Gaia-CRF represents a tiny fraction of the Gaia sources. With the typical angular distance between the quasars of about 6 arcminutes the Gaia-CRF is not dense enough to provide a suitable reference grid needed for forthcoming Extreme, Giant and Overwhelming telescopes but also for smaller instruments currently operating or being planned. Moreover, most of the quasars of the Gaia-CRF are rather faint (between magnitudes $G = 19$ and 21) so that the accessibility of the reference frame is given only in the optical and almost exclusively in that interval of magnitudes. The extension of the Gaia visible reference frame into the NIR is an important step given that so many new space and ground based observatories will have infrared sensitive instruments. A new mission would provide better accuracy to explore proper motion patterns, for example, from the Sun's Galactic acceleration to gravitation waves, real time cosmology and fundamental physics.

In summary, the new mission proposed to ESA in the Voyage2050 call (Hobbs, *et al.*, 2019a), will observe many new stars in obscured regions. We estimate at least 5 times as many stars will be observed, giving up to 8 billion new objects. NIR opens up a new wavelength range which allows us to probe the dusty obscured regions of the Galactic disk with high-precision astrometry and broad-band high-resolution photometry, while out of the Galactic plane a new mission will go deeper to enhance the halo science cases and provide complementary legacy data to ground based surveys such as LSST. A common astrometric solution for the two missions will give greatly improved proper motions but also improve the parallaxes, for up to 2 billion common stars. Long term maintenance and expansion of the dense and very accurate celestial reference frame with a new mission is necessary for future precise astronomical observations and provides an essential service for the astronomical community. These features ensure that a new mission is not simply an increment on the previous one but will create an astrometric revolution in itself!

2. THE TECHNICAL CHALLENGE

In 2016 Hobbs *et al.* proposed to ESA a new all-sky NIR astrometry mission, called GaiaNIR, which could realise the science cases discussed above. Such a NIR space observatory is however not possible today: it requires a new type of Time Delay Integration (TDI) NIR detector to scan the entire sky and to measure global absolute parallaxes. In 2017, an ESA study[1] of the GaiaNIR proposal already hinted that a US-European collaboration would be a possible route to make GaiaNIR science and technology a reality and subsequently McArthur *et al.* 2019 and Hobbs *et al.* 2019b submitted white papers to the US decadal survey (Astro2020) outlining the science cases and a possible US-European collaboration. The Australian National University is also developing NIR astronomical detector technology with TDI capabilities and are very interested in becoming part of this endeavour. The Japanese are currently working in a different direction with small-JASMINE, which has been recently selected by ISAS/JAXA for their M-3 mission with a current scheduled launch in mid-2020s, to do relative (to Gaia) astrometry in the NIR, but only focusing on the small region within ∼100 pc from the Galactic centre and relatively bright (Hw< 15 mag) stars. With their experience from small-JASMINE they are clearly interested in collaborating on the new mission outlined here.

In the Astro2020 APC white paper (Hobbs *et al.*, 2019b) investigated four different technologies which could be used to achieve our goals. Astronomical-grade infrared detectors are well established for both ground- and space-based applications. At shorter IR wavelengths, the premium detectors are HgCdTe devices, especially those fabricated by Teledyne in the USA. Unlike CCD detectors, the state-of-the-art for optical wavelengths, the HgCdTe devices cannot be used in a scanning mode, in which the image is transferred within the device synchronously with the scanning motion of the optical system (i.e. TDI). TDI is useful in many applications, and particularly for surveys, as individual exposures are not required, and data simply pour out of the detector array in a continuous stream. An example of TDI in ground-based astronomical applications is the Sloan Digital Sky Survey (SDSS), one of the most influential astronomy initiatives ever while a space-based example is ESAs Gaia mission mentioned above. Such surveys could not have been achieved without TDI operation but have been limited to the optical band.

This is a significant limitation. The importance of NIR in modern astronomy and cosmology is abundantly clear with most major ground-based facilities operating powerful infrared instrument suites, and major upcoming missions such as James Webb Space Telescope, Euclid and WFIRST

[1] `http://sci.esa.int/future-missions-department/60028-cdf-study-report-gaianir/`.

are either completely or significantly orientated to infrared observations. There is a compelling case, therefore, for an infrared detector that can operate in TDI. There are a number of possible approaches to developing TDI-NIR detectors:

1. Using HgCdTe Avalanche Photodiodes (APDs) with TDI-like signal processing capability. The challenge here is to scale the technology to large format arrays and ensure the dark current does not introduce unwanted noise at temperatures above 100 K.

2. Ge detectors due to the lower band gap can detect NIR radiation of longer wavelengths than possible with Si detectors. Clearly this technology is new but many of the manufacturing techniques developed for Si are also applicable to Ge and further development is needed to see if they can be used for our application with low noise in large format arrays.

3. A hybrid solution which uses a HgCdTe NIR detector layer bump bonded to a Si CCD. The idea is that the photons are detected in the surface NIR layer and transferred to the Si buried channel at each pixel. Charge can then be easily moved along the pixels of the same column in sync with the charge generation, thus achieving TDI. What is not known yet is how efficiently the charge can be transferred from the NIR detection layer to the Si CCD and if both materials can be operated at the same temperature.

4. Microwave Kinetic Inductance Detectors (MKIDs) are cooled, multispectral, single photon counting, multiplexed devices, capable of observation in the UV through to NIR. They measure the energy of photons at high frequency to within several percent making them ideal for TDI like operation. Whilst relatively new, small MKID arrays have already been utilised on ground-based telescopes for astronomy, demonstrating their potential.

The above list of has been ordered to reflect the suitability of each option; the APD detectors are currently seen as the best option; the Ge detectors are limited in wavelength to 1600 nm; the hybrid solution is technically complex; and the MKID solution requires cryogenic cooling. The APD solution is most promising and rapid progress is being made in developing large format arrays suitable for our application (see Gilbert *et al.*, 2019). Nevertheless there are still some technical challenges, namely 1) they exhibit large dark currents even at low gain while conventional HgCdTe detectors do not and 2) the visible response of the devices needs to be enhanced - normally achieved through substrate removal. It remains to be seen if these challenges can be overcome but APD development looks promising at this point.

3. REFERENCES

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