14. Testing modified gravity

SINCE ITS FORMULATION AND experimental confirmation in the early years of the 20th century, Einstein's theory of general relativity has been widely accepted as providing the best known description of gravity, on all spatial scales. However, various observations, starting with the flat rotation curves observed in most spiral galaxies, but now embracing the existence of large-scale structure in the Universe, demand an additional non-visible 'dark matter' component to fit the data.

At the present time, and despite much experimental effort, there has been no decisive detection of dark matter. This leaves open the possibility that some modified theory of gravity might explain these perplexing observations without this hypothetical dark matter.

MODIFIED NEWTONIAN DYNAMICS (MOND) is a theory originally proposed by Milgrom (1983) which attempts to account for these long-range gravitational effects without invoking dark matter.

Subsequent years have seen several developments on the theoretical side, notably the incorporation of MOND into more generalised theories of relativity. Meanwhile, the most straightforward versions of the theory have been ruled out by more rigorous observations, notably using precise timing effects in the neutron-star merger GW 170817 (Boran et al., 2018).

A convincing detection of dark matter would settle the question. But in the absence of such a dark matter detection, new tests which can discriminate between dark matter, and modified gravity, are highly desirable. One such family of tests probes the observational effects of gravity under conditions of very low accelerations.

PREVIOUS WORK on tests of MOND-like gravity over the past decade has hinted at deviations of the form expected from a MOND-like gravity. But the observations available to date have been of insufficient quality to conclude one way or another.

Gaia was expected to provide much improved prospects for such a test, based on the orbital behaviour of a number of very wide-separation binary stars.

For separations larger than about 5000 times the Sun–Earth distance (i.e. 5000 astronomical units), the stars in such a system have sufficiently small orbital accelerations – below about 10^{-10} m s^{-2} – to provide a direct probe of MOND-like theories. This minuscule acceleration can be compared to that experienced by a body at the Earth's surface, of about 9.8 m s^{-2}.

Several studies have already made use of the Gaia DR1 and DR2 data to make a start on the problem (amongst them El-Badry, 2019; Hernandez et al., 2019; and Pittordis & Sutherland, 2019).

BINARY, AND occasionally triple or even higher multiplicity star systems, form – over a range of separations – in the swirling gas clouds of dense regions of the interstellar medium. These can be density enhancements triggered by the passage of our Galaxy's rotating spiral density waves. If a binary forms with a small separation, their orbits can slowly spiral inwards until they eventually coalesce. Wider separation binaries can be slowly torn apart by external gravitational forces.

Systems with extremely short orbital periods, of days or even hours, are well known and widely studied. And there are various ideas of how very wide binaries can form. But there is no clear picture of how far apart binaries can survive as a gravitationally bound pair, i.e. while still maintaining a stable orbit around each other.

In our solar neighbourhood, Alpha Centauri A and B orbit each other every 80 years. They are separated by about 11 times the distance between the Sun and Earth (i.e. 11 astronomical units) at their closest approach. Many binary star systems are known with a much wider separation, yet still remaining gravitationally bound.

BACK IN 1937, Armenian astronomer Victor Ambartsumian calculated that a very wide binary, with its very weak gravitational bond, rarely breaks apart due to a single close encounter with another star, but rather as a result of numerous distant passages that each gently pull on the binary until it slowly evolves from being bound to being unbound.

Hubble Space Telescope (ESA/NASA)

Alpha Centauri A and Alpha Centauri B

Thus, an ultra-wide binary with a separation of 0.5 parsec (1.6 light-years, or 100 000 astronomical units) is likely to break up within about 100 million years. A binary with a separation of 0.1 pc (0.3 light-years) might survive for more than a billion years. At these enormous separations, two stars will be widely separated on the sky, with very long orbital periods, but sharing an almost identical space motion over millennia.

How then can two stars be recognised as a physical binary? Close binaries will generally be unusually close together on the sky, much closer than the average star density on the sky would imply. Careful monitoring of the their space motions or radial velocities over years or decades can hope to reveal their orbital motion, thus confirming their gravitational coupling.

But how can a *widely separated* binary be distinguished from two completed unrelated stars? Any orbital motion of a slowly orbiting wide-separation binary would require extremely accurate measurements to recognise. In other words, the wider a binary is, the more difficult it is to identify – and this has been a major barrier to discovering wide binaries in the past.

Gaia is in the process of identifying many thousands of very wide and ultra-wide binaries from their highly accurate space motions. Their properties will help to determine the most likely mechanism responsible for their formation, and their proper classification will allow for the sorts of tests necessary to confirm, or discard, MOND-like theories of gravity.

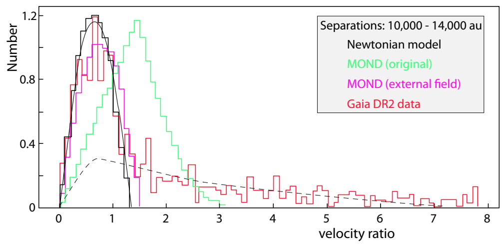
Returning, then, to the tests of gravity, it turns out that the original MOND-like models result in relative orbital velocities which are significantly different to those predicted by Newtonian models, specifically they can allow bound binaries with relative velocities well above the Newtonian 'ceiling'.

But MOND models including what is called an 'external field effect' (which are also preferred in present theories) give predicted relative velocities much closer to Newtonian, but do still show subtle but well-defined deviations in both their true space velocities, as well as in their projected velocities on the plane of the sky, as measured via the Gaia proper motions.

A high-velocity tail, well above the Newtonian prediction, could provide evidence favouring such a modified theory of gravity. And various studies suggested that there is also an optimal window of projected separation, between about 5–20 000 au, for the practical application of such a test.

Using the Gaia DR2 catalogue, Pittordis & Sutherland (2019) selected stars within 200 pc of the Sun, and bright enough ($G < 16$ mag) to give a good accuracy on the astrometry. They then selected pairs of stars with (projected) separations up to 40 000 astronomical units, using both the parallax and proper motion measurements to sift out nearly 25 000 plausible physical pairs.

They then calculated their likely orbits according to the various models (Newtonian, and MOND with and without an 'external field effect'), characterising them through some appropriate velocity ratio metric.



Pittordis & Sutherland 2019

Gaia wide binaries compared with theoretical models

The figure shown here is just part of their findings, covering only the subset of binaries with projected separations between 10 000–14 000 au. From the main peak of the observed histogram (in red), they found that the original MOND model (green) provides a very poor match to the observed data, while the inclusion of the 'external field effect' (purple) works much better.

The biggest surprise was a very long tail in the velocity ratio, across all of the separations observed. This long tail makes it impossible to decide between a Newtonian model, or a MOND model with an external field.

Pittordis & Sutherland (2019) found that this tail can be explained by pairs of stars which were born in the same open cluster, but which are currently undergoing a chance close 'flyby'. Clarke (2020) suggested that it can be attributed to a population of hidden triple systems.

In a similar study using Gaia DR2 data on 81 wide binaries, Hernandez et al. (2019) also found results consistent with Newtonian predictions below 7000 au, but inconsistent with it at larger separations.

While the principles of this sort of test have been demonstrated, the Gaia DR2 data are insufficient to rule on the reality or otherwise of a modified MOND-type gravitational field. The Gaia DR3 data will allow further advances. Meanwhile, it is clear that the Gaia data will have much to say about the formation – and eventual demise – of very wide-separation binary stars.