Messing around with gravity

Attempts to dispense with the need for galactic dark matter by altering the inverse square law of gravitational attraction have attracted a small but persistent advocacy.

THE simplicity of classical gravity, whether formulated according to Newton or to Einstein, is both pleasing and puzzling. It is pleasing because we want our physical theories to look good, but puzzling because we always then ask about the origin of the very simplicity that pleases us. To the questions why gravity should exist at all and why it should obey an inverse square law, Newton famously answered *hypotheses non fingo*, meaning (in the context) "Don't ask me". But this is plainly insufficient, at least for those physicists who spend their time trying out modifications to classical gravitational theories.

Newton's law can be amended (as in the case of the now defunct fifth force) to include some dependence on composition as well as mass, and small departures from the inverse square law are allowed on both the short and the long range. To Einstein's theory, which is the simplest nontrivial theory linking space-time curvature to the mass it contains, can be added not only the well-known cosmological constant but also terms containing higher derivatives of the curvature tensor. Physicists have made all these changes and more, and for more substantial reasons than mere curiosity.

One undisputed body of evidence that may indicate some need for a change to the laws of gravity comes from the measurement of galactic rotation curves. Radioastronomers can detect, beyond the visible limit of galaxies, faint hydrogen emission. By measuring the received wavelength of the Doppler-shifted 21-cm emission line, they can then plot the relative rate of rotation against distance from the galactic centre. From this simple exercise, first performed systematically by Vera Rubin and her colleagues in the 1970s, arises the odd result that galactic rotation tends to level off at some hundreds of kilometres per second — and to stay there.

Kepler's law says that the rotation velocity beyond the limits of a finite body of mass must fall off with distance, and conventional interpretation of a flat rotation curve is that there must be extra mass — dark matter — well beyond the point at which no light is seen from the galaxy. (This is the best evidence for dark matter in the Universe, but for all galaxies it adds up to substantially less mass than would constitute a critical cosmological density; whether there is enough dark matter to provide for that is another question.)

A priori, as the lawyers would say, one could equally well argue that if there is a conflict between one observation and another, the theoretical connection between them must be suspect. In this case, the flat rotation curve and the apparent absence of matter cause a problem only because of Kepler's law, which derives immediately from Newton's law of gravity. So why not change the theoretical law to leave the observations with their face-value interpretation? There is then no dark matter, but something must be done to the inverse square law.

For years, Mordehai Milgrom of the Weizmann Institute has been trying to make precisely this point. He has proposed changing Newton's law by adding to the usual definition of the force of gravity an extra term depending on the relative acceleration of the interacting masses. No reason is given for making this change, except to explain the rotation curves, but then Newton felt no need to justify his law beyond the fact that it explained the orbits of the Moon and planets — the Solar System's rotation curve, as it were.

Milgrom's theory asks for the gravitational force law to be slightly different when the acceleration is small, which then allows a different rotation curve to be obtained for the stately motion of gas a long way from the centres of galaxies. The occurrence of a term dependent on the acceleration is odd, but perhaps not so odd as it seems, because accelerations have absolute meaning (unlike velocities). On the other hand, Milgrom would have an abrupt change from normal to acceleration-dependent gravity at some suitably adjusted critical value of the acceleration, which makes his theory look untidy.

A more palatable modification of the inverse square law is to add a term reciprocal in distance (rather than the distance squared) that takes over only at large distances. Richard Liboff now explains in *Astrophysical Journal Letters* (**397**, L71; 1 October 1992) that even this is a little too simple, and cannot explain the whole range of galactic dynamical data. So Liboff attempts instead to make Milgrom's law tidier by including in the force law an acceleration term whose magnitude varies smoothly with distance. The particular mathematical form is entirely cooked up, following from no fundamental principle, but that is the spirit of this game.

Liboff's conclusion reinforces what Milgrom has been saying all along, that rotation curves can be explained with a modified gravity law, but goes beyond it in arguing that certain features of internal galactic dynamics, which gave Milgrom trouble, also fit with the generalized acceleration-dependent law. So why have physicists and cosmologists been ignoring Milgrom all these years, as they will undoubtedly now ignore Liboff? If the purpose is to explain galactic rotation curves, and if there is no other observational or experimental evidence bearing on the question, why is it acceptable to propose invisible, undetected and unidentified sorts of dark matter but, apparently, not quite seemly to fiddle with the inverse square law of gravity?

Part of the answer is that, in the modern idiom, the interactions between particles are perceived as somehow more elementary than the particles themselves. There are only four forces known to physics (three, if the weak and electromagnetic interactions are counted as having been successfully combined), but there are lots of apparently elementary particles. Theories that unify the forces further, or explain certain puzzling aspects of their symmetries and symmetry breakings, tend to create neater mathematical structures at the expense of adding to the storehouse of particles (Higgs bosons and axions come about in this way). That in turn suggests that it is safer to make up a new particle (dark matter) than to disfigure the mathematical form of a well-known force (as Milgrom's theory does).

Aesthetics thus account for some of the studied neglect of Milgrom's numerous papers, but there is also a more quantitative physical objection to his idea. Newton's law of gravity is successfully subsumed into Einstein's general theory of relativity, and a better understanding of the nature of gravity thereby provided. But nobody has yet found a modified form of relativity that incorporates Milgrom's theory; it remains an orphan in the classical world. And although there have been modifications of the simplest forms of Einstein's equations, none of them has so far proved relevant to the problem of galactic rotation curves. At the same time, it is hard to avoid the conclusion that any theory that leaves the workings of gravity untouched on small scales but makes changes on the scale of galaxies might be expected to imply more substantial changes yet on the cosmological scale.

The fact that Milgrom's theory of gravity has no relativistic counterpart is both an aesthetic flaw and a practical obstacle. It is more than slightly inconsistent to use general relativity to explain the Universe as a whole but a classical law of gravity that does not emerge from relativity to account for galactic dynamics. Until Milgrom has his own version of general relativity, his explanation of rotation curves must seem *ad hoc*. But then nobody has found any dark matter yet either.

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