

Dark Matter

1. What You See *Ain't* What You Got

Bikram Phookun and Biman Nath

Bikram Phookun is at the Department of Physics and Centre for Mathematical Sciences, St. Stephen's College, Delhi and is currently visiting the Raman Research Institute, Bangalore.

Biman Nath works at the Raman Research Institute, Bangalore, in the area of physical cosmology, in particular the intergalactic medium. He has written many popular articles on astronomy. His other interests include cinema, stamps and sketching.

The study of gas clouds orbiting in the outer regions of spiral galaxies has revealed that their gravitational attraction is much larger than the stars alone can provide. Over the last twenty years, astronomers have been forced to postulate the presence of large quantities of 'dark matter' to explain their observations. They are still in the 'dark' as to its true nature.

It is a little difficult to accept that ninety-nine percent of the universe is unobservable. There exists, however, a small tribe that has brought up a generation in this belief. Members of this tribe, known as astronomers, now take it for granted that over half of our Galaxy and most of the universe is composed of what they call dark matter – matter that is invisible but must exist (astronomers say) because of the influence it has on visible matter. Astronomers are more dependable than us laymen of course, as this article will show.

An astronomer's argument, in a nutshell, goes as follows – There are two independent measures of the matter in a galaxy or a cluster of galaxies: the amount of light given out by the system, and the gravitational force it exerts. The matter required to account for the gravity of the system is invariably more massive – sometimes a hundred times more massive – than the matter required to account for the light emitted by it. It is possible for matter not to emit light, but impossible for it not to interact gravitationally. Therefore, in every galaxy or cluster of galaxies, there is more matter than is visible. Since the universe consists of galaxies and clusters of galaxies, much of the matter in the universe is invisible, or dark.

In this article, we explain how the gravity of a spiral galaxy and

the light emitted by it can be used to discover dark matter. We have chosen the spiral galaxy to construct the argument for dark matter because it is the first astronomical object in which dark matter was shown to exist (though its existence was suspected earlier in clusters), and because the evidence in this kind of object is still the most convincing. (There are arguments as well for the existence of dark matter in clusters and in the universe as a whole; these will be presented in Part 2 of this article.)

How Light Maps Mass in a Spiral Galaxy

A spiral galaxy is seen as an agglomeration of a very large number of stars and some gas distributed in a rotating disk. In the Milky Way, a typical spiral galaxy, there are over 10^{11} stars distributed in a disk about 100,000 light years across and 3000 light years thick. The gas is mostly pure hydrogen, about half in atomic form, and of insignificant mass compared to the stars. Its radial extent is about twice that of the stars. The stars are visible in the usual sense of the term, i.e. they emit light in optical wavelengths. Most of the gas is visible through radiation in radio and other wavelengths; it contributes so little to the mass of the galaxy, however, that it may be neglected in accounting for the total mass. To a very good approximation, the visible galaxy is a rotating circular two-dimensional distribution of stars. The surface brightness (brightness per unit solid angle, or luminosity per unit area) of the disk is found in all spiral galaxies to decrease exponentially with radius: ($\mu(r) = \mu_0 \exp(-r/r_0)$).

When we make an image of a galaxy with an optical telescope what we observe is the distribution of light emitted by the stars in the galaxy. From this we must get the distribution of mass corresponding to the light-emitting matter. In the world of everyday experience this would be impossible: a black hippopotamus may emit less light than a glow-worm. A galaxy, however, does not consist of hippopotami and glow-worms, or anything as complex. Its constituents are much simpler – stars of a few types. The type of a star can be recognized by its spectrum, i.e. the variation with wavelength of light emitted. For example, the sun belongs to a

In the Milky Way, a typical spiral galaxy, there are over 10^{11} stars distributed in a disk about 100,000 light years across and 3000 light years thick.



Studies of stellar spectra lead us to believe, however, that within a single galaxy two collections of stars with similar overall spectra have similar population compositions and therefore similar mass-to-light ratios.

particular spectral type, and all stars of this type have similar masses and give out similar amounts of light; in other words, the mass-to-light ratio of all sun-like stars is constant. A randomly chosen patch of the galaxy will have a large number of different types of stars, and its mass-to-light ratio will be some average of the values for the different types. If the relative numbers of the different types of stars, i.e. the composition of the stellar population, is approximately the same in all parts of a galaxy, then its surface mass density, which we are looking for, is simply the surface brightness (luminosity per unit area) times the average mass-to-light ratio. But is the composition of the stellar population indeed the same throughout the galaxy?

To answer this question, we need to consider the variation with position of the spectral characteristics of a galaxy. Since two stars of the same type have similar spectra, it is clear that two collections of stars with the same relative numbers of different types of stars will also have similar spectra. From this we cannot conclude the inverse – that two collections of stars with different population compositions will not have similar spectra. Studies of stellar spectra lead us to believe, however, that within a single galaxy two collections of stars with similar overall spectra have similar population compositions and therefore similar mass-to-light ratios.

The actual value of the mass-to-light ratio to be used in a galaxy is not very important for our argument; what we are interested in is the distribution of mass. This we get, following the reasons given above, by simply multiplying the surface brightness by a reasonable mass-to-light ratio.

Gravitational Stability and Mass Distribution

Since a spiral galaxy, like the solar system, is a stable rotating system, we can use Newton's law of gravity to determine the speed $v(r)$ at which a star or gas cloud at a radius r must revolve about the centre. The procedure is similar to that used to calculate the speed of a planet in a circular orbit around the sun. (All planetary orbits, except Pluto's, are almost circular.) For stability, the centrifugal



force must be equal to the gravitational force, i.e.

$$mv^2/r = GMm/r^2 \quad (1)$$

In a galaxy m is the mass of a star or gas cloud at radius r , M is the mass of the galaxy out to radius r , and G is the universal constant of gravity. In the solar system m is the mass of a planet, r its distance from the sun, and M is just M_{sun} , which doesn't vary from one planet to another. Strictly speaking, (1) is true only if the mass distribution M is spherically symmetric or pointlike, but the error in applying it to the exponential disk of a galaxy is not large or of significance to the argument being presented here.

From (1), cancelling m , we get

$$v^2 = GM/r. \quad (2)$$

Since $GM(r)/r$ is the gravitational potential of the mass distribution, we may regard the rotation curve, i.e. the $v - r$ curve, as a representation of the potential itself. In the solar system, with $M = M_{\text{sun}}$, the gravitational potential has the well-known r^{-1} form, and the variation of speed from planet to planet depends on $r^{-1/2}$. In a spiral galaxy, M can be calculated as an integral in terms of the surface density. Fortunately, it is not necessary to work out this integral to understand the rotation curve. (The reader may work out the integral and show that the following reasoning is not incorrect.)

The exponential form of the surface mass density ($\Sigma = \Sigma_0 \exp(-r/r_0)$) in the disk of a spiral galaxy implies that its stellar mass is highly concentrated towards the centre; most of the mass is within the first two scale lengths of the exponential. Once we move away in radius from this central concentration of mass, the visible galaxy will begin to look, gravitationally speaking, more and more like a point mass. Its rotation curve beyond the inner portion will thus be similar in form to that of a point mass (see above). We may regard the central concentration of mass as a sphere of constant density, inside which v varies (as the reader can easily show) linearly with r . Putting the two together, we expect the rotation curve of an exponential disk of matter to rise linearly

All planetary orbits, except Pluto's are almost circular.

We expect the rotation curve of an exponential disk of matter to rise linearly out to some radius and then fall approximately as the square root of r .

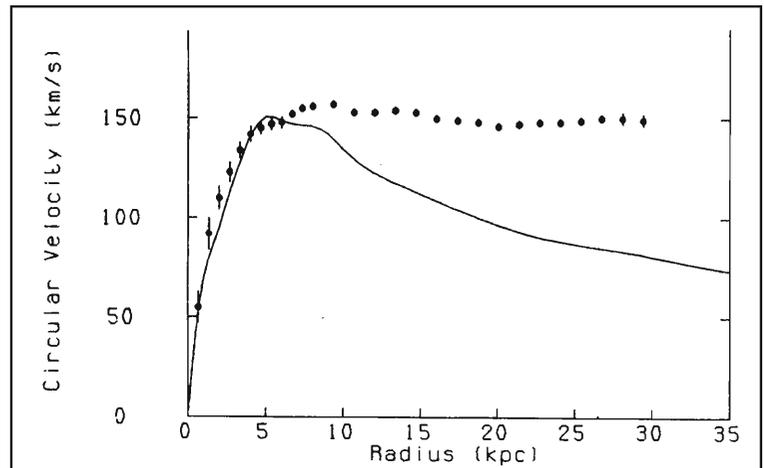
out to some radius and then fall approximately as the square root of r (see *Figure 1*).

The Rotation Curve Measurement and Findings

The rotation curve of a spiral galaxy can be measured using spectral lines from either the gas or the stars, using the idea of Doppler shifts: light emitted by an object moving away from or towards an observer is shifted towards longer or shorter wavelengths, respectively. In particular, a feature of the spectrum of light from an object, e.g. a spectral line, is shifted from the wavelength at which it appears when the object is at rest. This shift can be used to measure very accurately the speed with which the emitter is moving away from or towards the observer. All external galaxies, except our nearest neighbours, are observed to be moving away from us because of the expansion of the universe; so the Doppler shift usually measures the recession velocity rather than the velocity of approach.

The stars and gas from all parts of a galaxy emit spectral lines, whose Doppler shifts can be measured from the earth with great accuracy, even for very distant objects. Since the Doppler shift yields only the recession velocity of the source of light, its velocity vector cannot in general be determined. In a spiral galaxy, however, the stars and gas move, to a very good approximation, in circular orbits confined to a plane. For such orbits, given recession

Figure 1. A typical rotation curve of a spiral galaxy. The distance from the centre is measured in kiloparsec ($1\text{kpc} \approx 3 \times 10^{21}\text{ cm} \approx 3000\text{ light years}$). The dots are the observations. Note the flat behaviour at large radius. The continuous line is the expected behaviour if only visible matter were present. Note the $r^{-1/2}$ decrease.



velocity information over the entire galaxy, we can reconstruct the actual velocity field. Averaging the two-dimensional velocity field in annuli gives us the variation of v with r , i.e. the rotation curve.

Rotation curves of external galaxies were first observed on a large scale in the late sixties, using spectral lines from stars. A feature common to all galaxies was that their rotation curves rose more or less linearly with r for small values of r , and then remained almost perfectly flat, i.e. v remained constant as r increased. What this seemed to suggest (see (2)) was that the mass distribution of a spiral galaxy is such that M increases linearly with r . But this cannot be right if all the matter in the galaxy is in the form of stars, whose density falls exponentially with galactocentric radius. The implication of a flat rotation curve was simple but profoundly puzzling: surrounding the disk of stars there must be another distribution of matter that emits no light, i.e. dark matter. This seemed so farfetched at that time that astronomers began looking more carefully at their assumptions and arguments, to see if they could make this strange species of matter as *little visible* in their equations as it was in the sky.

The clinching argument for dark matter came a few years later. Using observations of Doppler shifts in the 21 cm spectral line of atomic hydrogen, which has a greater extent than the stars in a spiral galaxy, astronomers were able to obtain the rotation curves of galaxies well beyond the outermost extents of their stellar disks. Here too the rotation curves remained flat. (See *Figure 1*.) Now here was consternation: in any limited distribution of matter, visible or dark, the total mass must begin to level off after a certain radius. (The reader is encouraged to confirm that this is true for the exponential distribution of the stellar disk by performing the integration for M in the limit $r \rightarrow \infty$.) Spiral galaxies were thought for over half a century to be rotating disks of stars and gas – very interesting objects, no doubt, but ordinary in their constituents and distribution. Now astronomers were forced to conclude that the ordinary part of each spiral galaxy is embedded in a ghostly halo of dark matter that is not only invisible but seems to extend for ever.

All external galaxies, except our nearest neighbours, are observed to be moving away from us because of the expansion of the universe.



Now astronomers were forced to conclude that the ordinary part of each spiral galaxy is embedded in a ghostly halo of dark matter that is not only invisible but seems to extend for ever.

Dark Matter – Possibilities

There have been three reactions to the discovery of dark matter: (i) It doesn't exist; the law of gravitation must be modified so that the stars are all there is to a galaxy. (ii) Dark matter exists, but consists entirely of ordinary matter – Jupiter-like objects called *brown dwarfs* that are not massive enough to start the stellar energy-generating process of nuclear fusion that makes them visible. (iii) Dark matter not only exists but is exotic: it consists of neutrinos, or particles more extraordinary, and if we are smart enough we will be able to detect them some day.

Modifying the law of gravity is an extreme option. So far as we know, it works on all scales in all other circumstances. Furthermore, the modifications offered so far do not have the kind of breathtaking rightness and generality that new laws of nature usually do. (Readers are encouraged to experiment with changing Newton's law so that it can produce a flat rotation curve with an exponential distribution of matter but not to send the results of their efforts to the author or the editors.) Non-exotic brown dwarfs seemed until very recently the least revolutionary and most likely candidates for dark matter. They are not, however, completely invisible, just very dark; we expect them to show up on very-long-exposure images of otherwise blank portions of the sky. Such images have recently been made by the Hubble Space Telescope. Unfortunately, not enough brown dwarfs appear in them to account for all the dark matter needed. Another very interesting argument against brown dwarfs, based on Einstein's theory of gravitation, goes as follows – All massive objects act as gravitational lenses, which bend light as ordinary lenses do and thus focus light rays. If the light from a distant star is focussed by a gravitational lens passing between it and the observer, the star will scintillate, i.e. momentarily seem brighter. If there exists a large population of distant light sources, e.g. stars in the Large Magellanic Cloud, and a large population of intervening gravitational lenses, e.g. brown dwarfs in our Galaxy, we can calculate the expected number of scintillations, for a given population of background stars and foreground lenses. Such scintillations have been

looked for and, unfortunately, once again it is found that the frequency with which they are observed requires a smaller density of brown dwarfs.

Exotic dark matter may well exist, but at the moment it seems unlikely to solve the problem of dark matter in spiral galaxies. The best known variety of exotic dark matter is the neutrino. Neutrinos can be detected, though only with great difficulty. So far there is no evidence that they actually make up the dark matter needed on any astronomical scale. Furthermore, we know that they cannot form the dark-matter halos of spiral galaxies. This is because they are hot, i.e. they move with extremely high speeds with respect to each other. As a result, it is difficult for neutrinos to cluster and form halo-sized objects. (To understand this, consider the equilibrium between gravity and pressure that leads to a stable atmosphere around the earth. If the atmosphere is heated, it is more effective in resisting gravity, and tends to become more diffuse and extended in its distribution.) We shall not discuss other kinds of exotic dark matter since very little can be said at the moment about them.

What then is dark matter? A lot of people are trying to find out, but no one has a definitive answer yet.

Suggested Reading

- [1] V Jayant Narlikar, *The Lighter Side of Gravity*, Cambridge University Press, 1996.
- [2] V Jayant Narlikar, *The Primeval Universe*, Oxford University Press, 1988.
- [3] N Cohen, *Gravity's Lens: views of the new cosmology*, Wiley and Sons, 1988.
- [4] Virginia Trimble, *Existence and Nature of Dark Matter in the Universe*, *Annual Review of Astronomy and Astrophysics*, 25, 425, 1987.

Websites

1. <http://www-thphys.physics.ox.ac.uk/users/EamonnKerins/dark.html>
2. http://cosscc.gsfc.nasa.gov/gamma/new_win/nw5.html
3. <http://www.astro.queensu.ca/~dursi/tutorials.html>

Address for Correspondence

Bikram Phookun
Department of Physics and
Centre for Mathematical
Sciences, St. Stephen's
College, Delhi 110 007, India.
(Currently visiting
Raman Research Institute
Bangalore 560 080.)
E-mail: bikram@rri.ernet.in

Biman Nath
Raman Research Institute
Bangalore 560 080, India.