Dark Matter in Galaxies

Dark matter in spiral galaxies

SPIRAL GALAXIES are flat rotating systems. The stars and gas in the disk are moving in nearly circular orbits, with the gravitational field of the galaxy providing the inward acceleration required for the circular motion. The rotation of these galaxies is usually not like a solid body: the angular velocity of the rotation typically decreases with radius. To a fair approximation, assuming Newtonian gravity, the rotational velocity $V(r)$ at radius r is related to the total mass $M(r)$ within radius r by the equation $V^2(r) = GM(r)/r$, where G is the gravitational constant.

The radial variation of the rotational velocity (the rotation curve) is most readily measured from the gas in the disks. The emission lines of ionized gas in the inner regions are measured with optical spectrographs. With radio synthesis telescopes, rotation curves can be measured from the neutral hydrogen (H I) which emits a narrow spectral line at 1420 MHz (21 cm wavelength). The interest in measuring rotation curves of spiral galaxies is that they give a direct measure of the radial distribution of the total gravitating mass.

Until the early 1970s, most of the rotation data for spirals came from optical observations which did not extend beyond the luminous inner regions. At that time, the optical rotation curves seemed consistent with the distribution of luminous matter. With the construction of RADIO TELESCOPES like the Westerbork Radio Synthesis Telescope in The Netherlands, it became possible to measure the distribution and rotation of the H I in spiral galaxies. It was soon discovered that the H I in many spirals extended far beyond the starlight, and that the H I rotation curves in such galaxies often showed nearly constant rotational velocity out to the radial limits of the data.

This was unexpected, because a flat rotation curve means that the total mass of the spiral within some radius r increases linearly with r, while the total luminosity approaches a finite asymptotic limit as r increases. It soon became clear that a large amount of invisible gravitating mass (more than 90% of the total mass in some examples) is needed to explain these flat rotation curves.

The problem is illustrated in figure 1. The rotation curve comes from H I observations of a well studied spiral, NGC 3198. The curve labelled *disk* is the rotation curve that would be expected if the surface mass density in this galaxy were proportional to the light distribution shown in the upper panel. In this analysis, the constant of proportionality (the ratio of mass to light) was made as large as possible, with the criterion that the total expected rotation curve should not exceed the observed rotation curve. The gas in the galaxy also contributes to the expected rotation curve, as shown by the curve labelled *gas* (see also GAS IN GALAXIES). The contributions to the expected rotation curve from stars and gas must be added in quadrature to derive the total expected rotation curve. From the curves in this figure, there is no way that the stars
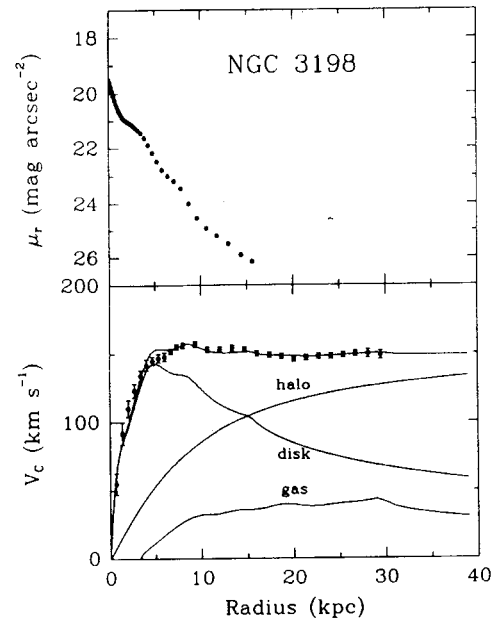

Figure 1. The upper panel shows the R-band radial surface brightness distribution of the spiral galaxy NGC 3198. The lower panel shows its H I rotation curve (points). The curve labelled *disk* shows the expected rotation curve if the surface density distribution followed the surface brightness distribution in the upper panel. The curve labelled *gas* is the contribution to the rotation curve from the observed gas. Together, the gas and the disk cannot reproduce the observed flat rotation curve at large radius. An extra gravitating component, the dark halo, is needed. The curve labelled *halo* is the rotation curve of the adopted dark halo model: the three labelled rotation curves, when added in quadrature, produce the total rotation curve that passes through the observed points. (From Begeman K 1987 *PhD Thesis* University of Groningen.)

and gas together can produce the flat observed rotation curve. An additional massive and extended distribution of dark matter is needed. The rotation contribution for a simple dark halo model is shown in the figure: the model is chosen so that the dark halo plus disk plus gas together give the rotation curve that passes through most of the observed points in the figure. At the radial limit of the data, the dark halo is providing most of the total gravitational field.

The halo model in figure 1 is a minimum halo, in the sense that the contribution of the disk to the rotation curve was made as large as possible. If a lower mass-to-light (M/L) ratio had been adopted for the disk, then a more centrally concentrated halo would be needed to make up the larger discrepancy between the observed and expected rotation curves. It is difficult to measure the M/L ratio for disks independently of the rotation curve itself, and there is still a lot of controversy about the correctness of the maximum disk approach as shown in figure 1.

The situation shown in figure 1 is typical of almost

all DISK GALAXIES that have extended H I distributions, including the small DWARF IRREGULAR GALAXIES that are also in rotational equilibrium. In almost every example, a massive dark halo that dominates the enclosed mass $M(r)$ at large r is needed to explain the observed rotation curves. The nature of this dark matter remains unknown (see DARK MATTER: ITS NATURE), and is one of the great problems of modern astrophysics.

For decompositions as shown in the figure, the dark halo is often modelled for simplicity as a spherical system with a radial volume density distribution of the form $\rho(r) = \rho(0)/(1 + r^2/a^2)$, where a is a scale length and $\rho(0)$ the central density. This particular distribution is chosen because it generates a flat rotation curve at large radius.

The spherical shape is simply an assumption. It turns out to be very difficult to measure the shapes of dark halos. The thin neutral hydrogen layer in edge-on spirals is observed to flare beyond the edge of the stellar disk, where the vertical restoring force of the disk is reduced. The extent of this flaring can be used to estimate the flattening of the dark halo (a flat halo would lead to less flaring). Another idea is to study the POLAR RING GALAXIES, in which material is rotating in two orthogonal planes so the gravitational field in both planes can be measured. Both of these approaches have uncertainties, but they hint that dark halos may be significantly flattened.

In figure 1, the gently rising rotation curves for the halo and for the gas are roughly similar in shape out to the radial limit of the observations. This is again typical for disk galaxies with extended H I distributions, and hints that the gas and the dark matter distributions are in some way closely related. Some authors have argued that the dark matter may be in the form of cold gas, but this remains contentious.

Dark matter in our Galaxy

Although our location in the disk of our Galaxy makes it difficult to measure its rotation curve out to large radius, other less secure mass estimators become possible in this situation. For example, the velocities of halo stars out to distances of 100 kpc from the Sun can be used to estimate the total galactic mass. Some halo stars pass through the solar neighborhood at velocities in excess of $600 \, \mathrm{km \, s^{-1}}$. If these stars are bound to the Galaxy, then they provide another mass estimator. The ANDROMEDA GALAXY, at a distance of 770 kpc, is approaching the Milky Way at about 120 km s^{-1}, which provides yet another mass estimator by assuming that the combined mass of the two galaxies is sufficient to turn around their initial expansion within the lifetime of the universe. All of these estimators together indicate that the enclosed mass of the Milky Way increases linearly with radius out to at least 150 kpc and that its total mass is about $15 \times 10^{11} M_{\odot}$. The luminous mass is unlikely to exceed $1.2 \times 10^{11} M_{\odot}$, so the mass of our Galaxy is probably more than 90% dark.

If the dark matter is in the form of compact objects of stellar or substellar mass (e.g. jupiters, white or brown dwarfs, neutron stars), then dark halo objects passing between the observer and a distant star cause the distant star to brighten as they pass, through GRAVITATIONAL LENSING. The duration of the brightening depends on the mass and velocity of the lens and the geometry of the event. For stars in the MAGELLANIC CLOUDS, the typical duration of the brightening would be a few months for dark halo objects of solar mass. Several groups have attempted to detect dark objects in this way. The MACHO experiment monitored the brightnesses of several million stars in the LMC over a period of about 7 years, and has detected about 15 lensing events. If these lensing objects lie in the galactic halo, then they provide about half of the total dark matter and their individual masses are about $0.5 M_{\odot}$. This mass is typical of white dwarfs and suggests that these dark objects could be old WHITE DWARFS, perhaps remnants of a very early and very massive burst of star formation. There is no evidence for a significant population of luminous stars associated with the dark halo, so a rather special stellar mass function would be needed to produce large numbers of old white dwarfs without producing even larger numbers of old luminous stars. It remains possible that the lenses are not in the galactic halo. For example, if the LMC is sufficiently extended along the line of sight, the lenses could be objects in the LMC lensing other objects in the LMC.

Dark matter in elliptical galaxies

The evidence for dark matter in disk galaxies is secure because their dynamics is so simple. ELLIPTICAL GALAXIES are not supported by rotation, so rotation curves cannot be used to study their dark matter content. Other dynamical mass indicators are needed. Some of the largest ellipticals are embedded in an envelope of hot x-ray emitting gas. If the radial temperature distribution of this hot gas is known, its hydrostatic equilibrium can be used to measure the total mass of the parent elliptical. The motions of stars, globular clusters and planetary nebulae in the outer regions of elliptical galaxies can also be used to estimate their masses, although this requires some assumptions about the orbits of these tracer objects. The weak gravitational lensing of background galaxies provides an interesting and independent statistical way to measure the dark matter content of elliptical and disk galaxies.

The evidence indicates that the largest elliptical galaxies contain substantial amounts of dark matter. We can use the mass-to-light ratio as a useful measure of the dark content of a galaxy. An old stellar population without dark matter has a mass-to-light (M/L) ratio of about 5 in solar units, depending on its metallicity. Disk and elliptical galaxies can have M/L ratios as high as $\sim$80. Some of the smallest elliptical galaxies, the dwarf spheroidal companions of the Milky Way, show very high dark matter content, with M/L ratios $\sim$100. For these systems, the masses are estimated from velocities measured for many individual stars. Again, some assumptions about the stellar orbits are needed.

Formation of dark halos

In the current picture of GALAXY FORMATION, clumps of dark matter mixed with baryons come together to form a galaxy. The nature of the dark matter is unknown, but it is believed to be non-dissipative. The dark halos then gradually build up into weakly flattened spheroidal structures while, in disk galaxies, the rotating baryons dissipate into flat disks in near-circular motion within their dark halos. There are now enough data on dark halos to determine how their properties change with the brightness of the visible galaxy. It turns out that the faintest galaxies have the densest dark halos, about 1000 times denser than the dark halos of the brightest galaxies. This indicates that the halos of lowest mass emerged first from the expanding universe, when the density of the universe was high, as expected from theoretical arguments.

For more information on dark matter in the universe, see the article on GALAXY CLUSTERS.

Bibliography

For a useful recent overview of work on dark matter in galaxies see

Persic M and Salucci P (ed) 1997 *Dark and Visible Matter in Galaxies (ASP Conf. Ser. 117)* (San Francisco: Astron. Soc. Pacific)

Ken Freeman