MASSES OF GALAXIES

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Summary

Gravitational forces in the outer regions of galaxies are too large to be produced by observable stars and gas. The preferred interpretation of this effect is that ~90% of the mass in galaxies is in the form of a dark, spheroidal halo of unknown composition. A generous dark-halo model leads to $\Omega(\mathrm{gal}) \lesssim 0.1$. Galaxies therefore could either be baryonic or nonbaryonic, and the mass in galaxies may suffice to explain the dynamics of the Universe on scales of $\lesssim 10^1$ Mpc (on the $H_0 = 50$ km s^{-1} Mpc^{-1} scale).

Galaxies and the "Island Universe" Concept

On deep images of the sky at optical wavelengths, galaxies usually appear to be spatially well separated. Exceptions occur in dense clusters and groups of galaxies, which contain only a small fraction of the total galaxy population. Thus Hubble's 1936 picture of the Universe at *optical* wavelengths of light remains essentially correct: "The Universe is empty for the most part, but here and there, separated by immense intervals, we find other systems comparable with our own [galaxy]."[1] With data that now cover most of the electromagnetic spectrum, this model can be generalized; almost all of the matter which observably interacts with photons at the present epoch is concentrated into galaxies.

A simple hypothesis is that most of the mass in the current Universe resides within the optically detectable boundaries of galaxies. The internal dynamics of galaxies are then predictable from the measured spatial distributions of luminous matter in galaxies. For example, optical/infrared telescopes can trace the spatial brightness profiles of stellar populations from their thermal photon emissions, and radio telescopes can map interstellar gas distributions from microwave emission lines. The results of these exercises show that the spatial extents of stellar components of galaxies are not much larger than those measured 30 years ago, but many galaxies have HI gas at up to twice the optical dimensions.[2,3] However, the additional luminous mass fraction inferred for these extended components of most galaxies is small. Most of the luminous mass in giant spiral and elliptical galaxies lies within the visible optical dimensions, and the *total* sizes of galaxies are much less ($\lesssim$0.1) than the mean separations between giant galaxies in the vicinity of our Milky Way (~1 Mpc). Galaxies still *appear* to be well-separated baryonic islands in an essentially empty intergalactic sea.

Flat Rotation Curves

Conversion of the measured projected light distributions of galaxies into dynamical models involves a number of assumptions. Luminosity densities are transformed into the required mass densities via an adopted mass-to-light ratio (M/L). This is tricky since most of the mass in a tyical stellar population is hidden in intrinsically very faint, dwarf stars that can only be observed in the *immediate* vicinity of the Sun (within our local Galactic disk, $r \lesssim 100$ pc). Once the stellar M/L is known (it ranges from 1–10, depending on the evolutionary state of the stellar population), a three-dimensional mass model must in general be devised in order to derive the gravitational potential within the galaxy.[4]

Fortunately, many spiral galaxies are well approximated by a thin, axisymmetric disk model. For contant M/L, the luminous surface mass density can be fit wih an exponential law, $\sum^* = \sum_0^* \exp(-\alpha\ r)$. In typical spirals, the optical boundary occurs at a radius of $\sim 3\alpha^{-1}$ to $5\alpha^{-1}$.[5] This simple model predicts that the circular orbital velocity V(r) of a test particle within the disk will decline to ~ 0.7 of its peak value near the optical edges of galaxies. Furthermore, the radial gradient of V(r) by this point should begin to approach its asymptotic Keplerian value.[5]

More sophisticated models for galactic mass distributions yield qualitatively similar results; V(r) should decrease near the optical limits of galaxies.[6] Unfortunately, galaxies are faint, with typical peak optical surface brightnesses that are roughly equal to the surface brightness of the dark night sky. Thus when astronomers had to rely on photographic techniques to record spectra for measuring galactic V(r) rotation curves from Doppler shifts, it was difficult to extend the data much beyond radii of $\sim 2\alpha^{-1}$ in spirals. These data seemed to show a decrease in V(r) in the outer parts of spirals, as predicted by the models. Results from this pleasant era are summarized by Burbidge and Burbidge, who were careful to point out the many limitations imposed by the then available observations.[7]

With the advent of better spectrographs coupled to electronic detectors in the early 1970s, it became possible to extend optical V(r) measurements over the entire visible dimensions of many galaxies.[8] At approximately the same time, radio telescope technology improved to the point where V(r) could be determined from HI-line Doppler shifts to beyond the optical edges of some galaxies.[3,9] The results were surprising. Rotation curves of spiral galaxies do not decline at large radii; instead, V(r) $\simeq$ constant in most cases to the end of the data.[4,10]

Massive Dark Halos

In order to explain flat rotation curves, we can either postulate the existence of a spatially extended, nonluminous "dark matter" component in spiral galaxies,[4] or assume that there are problems with Newtonian physics on large spatial scales.[11] The former view has been adopted by most astronomers. Dark mass has a long history in Galactic and extragalactic astronomy, and we should not be surprised to find that it plays a role in the global dynamics of galaxies.[12] In 1932 Oort showed that velocity dispersions of stars perpendicular to the galactic disk are too large relative to their z scale heights to be explained by the density of luminous matter.[13] This local dark matter problem has stubbornly refused to disappear and is an important indication that dark matter exists even in dissipational structures, such as the Galactic disk.[14]

The 1980's standard model of a giant spiral galaxy produces a flat rotation curve by including a massive, spheroidal dark halo.[4,6,8,10] The luminous part of the system is pictured as being deeply embedded within the more extensive massive halo. A spheroidal distribution is favored for the dark matter for several reasons: (1) A dynamically hot, massive halo stabilizes galactic disks against bar mode instabilities, which are absent in about one-half of all spiral galaxies.[15] (2) A flat rotation curve is naturally produced by an isothermal sphere, which will have $M(r) \alpha\ r$ as in spiral galaxies, and this may be a preferred form for the formation of a massive galactic halo.[16] (3) Outer gas disks of spirals are often noncoplanar, and this phenomenon is most easily understood if a spheroidal dark halo is present.[17]

The radial extent of dark matter bound to individual spiral galaxies is poorly determined. Normal probes of galactic gravitational potentials become too scarce by radii of ~30 kpc ($\sim 5 - 10\alpha^{-1}$) in a typical spiral to be useful. Early hopes that binary galaxies would readily cover this gap have been dashed by the discovery of serious problems with sample selection effects, and similar problems also lower the precision of masses derived from dynamics of small groups of galaxies.[18,19] However, even if galaxies originally had very extensive halos, collisions with other galaxies would remove outer dark envelopes, rapidly in dense clusters of galaxies[20] and probably more slowly in low-density regions.[21] Based on the current data, a generous assumption is that all giant spiral galaxies have dark halos extending to ~10 times their optical radii; thus the total mass exceeds the optical mass by about a factor of 10. In terms of M/L, we are taking M/L = 100 for the typical spiral ($H_0 = 50$).

The spheroidal dark-halo model is supported by other probes of galactic gravitational potentials that can be applied to diskless, giant elliptical as well as spiral galaxies. The velocities of globular star clusters and the structures of hot, spheroidal gaseous atmospheres of elliptical galaxies also suggest the presence of canonical massive halos,[22,23] although there are controversies about some of these methods.[24] A modern model then is that giant galaxies resemble icebergs more than islands; we see only the insignificant tips of the mass distributions in luminous matter.

Small Galaxies

Most of the optical light in the Universe is produced by giant galaxies, but the most numerous galaxies are small dwarf systems. Faber and Lin suggested that dwarfs contain similar amounts of dark matter as giants, and this view has received some observational support.[16,25] Due to the low internal velocities in dwarfs, it is very difficult to accurately determine total masses, and thus it is hard to define the dwarf galaxy dark matter problem. The tendency for dwarfs to exist in chaotic states further complicates the interpretation of even good kinematic data.[26] These problems will probably be sorted out over the next few years, but the available data do rule out the very high M/L values ($M/L \gg 100$) that would be needed for dwarf galaxies to make substantial contributions to the cosmological mass density.

Cosmological Implications

(1) The cosmic luminosity density of galaxies is reasonably well known, and thus can be used to find $\overline{\rho(\mathrm{gal})}$ from our choice of $M/L = 100$ ($H_0 = 50$).[27] Closure requires $M/L \sim 10^3$, and thus we see that $\Omega(\mathrm{gal}) \lesssim 0.1$.[27,28] Mass bound to individual galaxies with constant $M/L = 100$, i.e., with large dark halos, cannot give $\Omega_0 = 1.0$.

(2) Theoretical predictions of big bang nucleosynthesis, when compared with observed abundances of light elements, set a limit on the present mass density in nucleons of $\Omega(N) \lesssim 0.2$.[29] As G. Steigman has emphasized, galaxies therefore are not *required* to have nonbaryonic mass components to fit within the standard cosmological model. Whether baryons can be hidden in sufficient amounts to meet the conditions set by galactic dynamics, however, is an unsettled problem, and the presence of large amounts of nonbaryonic mass cannot be excluded.[30]

(3) The mass in galaxies may be sufficient to explain the dynamics of the local Universe on scales of $\lesssim 10^1$ Mpc. On the scale of the Local Supercluster ($\sim 10^1$ Mpc), $\Omega = 0.1$–0.3 is needed to produce our peculiar infall velocity; so extra mass beyond that in galaxies could be present,[27,28] and the situation seems to become more severe on larger spatial scales.[31] The question of relationships between dark matter in galaxies and the possible existence of diffusely distributed dark matter in the Universe thus continues to be of interest.

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