DOES OUR GALAXY HAVE A MASSIVE DARK CORONA ?

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Abstract. The rotation curves of spiral galaxies indicate that most of them have massive dark coronas, and it seems likely that our Galaxy also has a dark corona. Our position in the galactic disk makes it difficult to measure the galactic rotation curve beyond about 20 kpc from the galactic center, but it does allow us to use several other indicators of the total galactic mass out to very large distances. I will review some of these indicators. The conclusion is that the Galaxy does indeed have a massive dark corona: the data are consistent with the enclosed mass within radius R increasing like $M(R) \approx R(kpc) \times 10^{10}\ M_{\odot}$, out to a radius of more than 100 kpc, and a total galactic mass of at least $12 \times 10^{11}\ M_{\odot}$.

1. Introduction

The rotation curves of disk galaxies, measured from the kinematics of the interstellar gas, give a fairly direct measurement of the radial component of the gravitational field within the disk. In the inner regions of spiral galaxies (out to two or three radial scalelengths of the underlying stellar disk), the rotation curves can be well modeled by the gravitational field of the visible matter (including the gas itself). This does not work for the more extended HI rotation curves which, in many spiral galaxies, can be measured out to many disk scalelengths. In almost all such spirals, the rotation curves remain flat or rise with radius. This provides very strong evidence for the existence of a massive dark corona: see Freeman (1993) for a review. The inferred mass of this dark corona is typically 5 to 10 times the mass of the underlying stellar component. The dynamics of galactic rotation is relatively simple, and it is difficult to see how this inference about the

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existence of the massive dark coronas could be conceptually wrong, unless the adopted inverse square law of gravity is not correct in the outer regions of galaxies (eg Milgrom, 1988).

Dark coronas are detected in almost all spirals with extended rotation curves, so it seems very likely that our Galaxy also has a dark corona. The sun's position in the galactic disk makes it very difficult to measure the rotation curve of our Galaxy beyond about 20 kpc from the galactic center, so other less direct methods are needed to establish the extent and properties of the galactic dark corona.

The flat rotation curves usually seen in large spirals indicate that the galactic mass $M(R)$ enclosed within radius R increases linearly with R. We will review some of the methods that have been used to estimate the $M(R)$ distribution of the Galaxy. If the Galaxy has no dark corona, then the $M(R)$ distribution should approach the total mass of the (disk + bulge + stellar halo) for large R. So first we briefly discuss the mass of the visible components of the Galaxy.

2. The Mass of the Visible Components of the Galaxy

The mass of the visible components of the Galaxy lies mainly in its bulge and disk, with a small contribution from the metal-poor stellar halo.

- The DIRBE photometry of the galactic bulge (Dwek *et. al.*, 1994) gives a bulge mass of about $1.3 \times 10^{10}\ M_\odot$. This is consistent with Kent's (1992) dynamical estimates.
- The mass of the galactic disk is not well known, because (*i*) the local circular velocity, the scalelength and the local surface density of the disk are all still uncertain, and (*ii*) the parameters of the dark corona itself are uncertain, so we do not know how much the dark corona contributes to the circular velocity in the inner regions of the Galaxy. For this discussion, we adopt a circular velocity of 220 km s^{-1} near the sun, and take the radial scalelength of the disk to be 4.5 kpc (see for example Lewis and Freeman, 1989). For a bulge mass of $1.3 \times 10^{10}\ M_\odot$, the maximum disk mass consistent with this local circular velocity is about $11 \times 10^{10}\ M_\odot$, corresponding to a total surface density near the sun of about 130 $M_\odot$ pc^{-2}. This value for the local surface density is much higher than the recent dynamical estimates: these are mostly around 50 $M_\odot$ pc^{-2} (*eg.* Kuijken and Gilmore, 1989), and correspond to a total disk mass of only about $4 \times 10^{10}\ M_\odot$.
- Recent studies of the metal-poor stellar halo of the galaxy indicate that its mass is about $1 \times 10^9\ M_\odot$ (*eg.* Morrison, 1993); the stellar halo does not make a significant contribution to the galactic gravitational field.

We conclude that the total mass of the disk, bulge and metal-poor halo is probably in the range $(5 \text{ to } 12) \times 10^{10}\ M_\odot$. If the correct value is at the low end of this range, then the dark corona is already making the dominant contribution to the circular velocity at the galactocentric radius of the sun.

3. The Galactic Rotation Curve

Data on the galactic rotation curve are reviewed by Fich and Tremaine (1991). For an adopted local circular velocity V_c of 220 km s^{-1} and solar radius $R_\circ$ of 8.5 kpc, the mean rotation curve is roughly flat for R between about 3 kpc and 15 kpc. Beyond 15 kpc the velocity uncertainties become large and the rotation curve less secure. Merrifield (1992) extended the HI rotation curve by using the thickness of the galactic HI layer as a distance indicator: he adopts $(R_\circ, V_c) = (7.9 \text{ kpc}, 200 \text{ km s}^{-1})$ and finds that the rotation curve is slowly rising all the way from $R = 2$ kpc to the maximum extent of the measured rotation curve at 20 kpc.

The galactic rotation curve out to a radius of 20 kpc gives a total $M(20\ kpc) = 22 \times 10^{10}\ M_\odot$. This is at least double the estimated mass of the visible components of the Galaxy, and already provides a strong indication that the Galaxy has a dark corona. In some spirals it is possible to estimate the parameters of the dark corona (*eg.* its core radius and scale density) from the shape of the rotation curve; for the Galaxy this is difficult, because the rotation curve itself remains uncertain in the inner few kiloparsecs of the Galaxy.

4. The Escape Velocity in the Solar Neighborhood

In the solar neighborhood, stars of the metal poor stellar halo have a velocity dispersion of about 140 km s^{-1} in the radial direction: see for example Morrison *et. al.* (1990). If the halo stars in the high velocity tail of the velocity distribution are bound to the Galaxy, then their distribution of total space motions gives a lower limit on the local escape velocity V_{esc} which in turn sets a lower limit on the total galactic mass.

The mass estimates from escape velocity arguments are lower limits on the total mass because the estimated V_{esc} may be smaller than the true escape velocity in the solar neighborhood. For example, the most energetic halo stars in the solar neighborhood may be firmly bound to the Galaxy if the stars of the halo come from accreted satellites or if the velocity distribution of the halo stars has been truncated in the close approaches of the Magellanic Clouds.

Cudworth (1990) remeasured the proper motions for 9 of the highest velocity halo stars from the sample of Carney *et. al.* (1988), and found that the largest stellar space motion in the sample was about 475 km s^{-1}.

Leonard and Tremaine (1990) used a maximum likelihood analysis to estimate V_{esc} from the velocity distribution of the highest velocity stars. Their analysis included the observational biases associated with the proper motion selection criteria for high velocity stars. They found that the 90% confidence limits on V_{esc} are 450 and 650 km s^{-1}. The radial velocity alone of one particular high velocity star gives a limit of $V_{esc} > 430$ km s^{-1}.

For a simple galactic mass model (*eg.* Carney *et. al.* 1988) with $M(R) \propto R$ out to some limiting radius R_{lim} and constant for $R > R_{lim}$, the total mass M_{total} is related to the local escape velocity V_{esc} by

$$\log M_{total}/M(R_\circ) = (1/2)(V_{esc}/V_c)^2 - 1$$

where $R_\circ$ and V_c are again the radius of the solar orbit and the circular velocity. With this model, the Leonard and Tremaine estimate of V_{esc} indicates that $M_{total} > 3 \times 10^{11}\ M_\odot$.

5. Distant Stars and Satellites

The radial velocities V_{rad} and distances d of distant stars, globular clusters and satellites can be used to provide another estimate of $M(R)$, if we assume that these objects are test particles at random orbital phases in an isolated Galaxy. The mass estimates depend on the adopted orbital properties of the tracer population (*ie.* on the isotropy or anisotropy of the velocity ellipsoid). Hartwick and Sargent (1978) derived a galactic mass $M(60kpc) = 8 \times 10^{11}$ $M_\odot$, assuming isotropic orbits for their tracer satellites. Little and Tremaine (1987) used the radial velocities and distances of distant objects to estimate the galactic mass for two approximations to the galactic mass distribution:

- for a point mass approximation, the observed distribution of (dV_{rad}^2/G) gives an estimate of the total galactic mass;
- for a very extended halo with $M(R) \propto R$, the observed distribution of V_{rad}^2 provides an estimate of the (constant) circular velocity V_c.

Zaritsky *et. al.* (1989) and Norris and Hawkins (1991) applied the Little and Tremaine method to samples of distant blue horizontal branch stars, globular clusters and satellite galaxies. The point mass approximation gives a mass $M > 11 \times 10^{11}\ M_\odot$ if the orbits of the tracers are isotropic. The extended halo approximation gives $V_c \approx 185 \pm 20$ km s^{-1} and the enclosed mass $M(50\ kpc) = 4 \times 10^{11}\ M_\odot$, again assuming isotropic orbits. Sommer-Larsen *et. al.* (1994) argue that the stellar orbits in the outer halo are probably more tangential than isotropic; if this is correct, then these mass estimates would be lower limits. Tracers with galactocentric distances between about 20 and 40 kpc give similar values for V_c.

Lin *et. al.* (1995) used the observed proper motion and radial velocity of the LMC and arguments about the dynamics of the Magellanic Stream to constrain the mass of the Galaxy. They find that $M(100\ kpc) = (5.5 \pm 1) \times 10^{11}\ M_\odot$. This estimate is about half of the mass given by the timing arguments (see the next section) out to similar galactocentric distances.

6. Timing Argument

M31 lies about 710 kpc from the Galaxy and has a galactocentric radial velocity of -118 km s^{-1}. These two galaxies are the dominant objects in the Local Group. If their initial separation is small, then adopting an age for the universe and assuming radial orbits gives a lower limit on the total mass of (M31 + Galaxy) from simple Keplerian arguments (Kahn and Woltjer, 1959). For an age of 18 Gyr, this limit corresponds to a galactic mass of $(13 \pm 2) \times 10^{11}\ M_\odot$. (The ratio of the masses of M31 and the Galaxy is estimated from their observed rotational velocities).

Another timing estimate comes from the dwarf galaxy Leo I, at a distance of 270 kpc (Zaritsky *et. al.* 1989; Lee *et. al.* 1993). This gives a galactic mass of $(12 \pm 2) \times 10^{11}\ M_\odot$. The two estimates from M31 and Leo I agree remarkably well, and are consistent with a flat rotation curve ($V_c = 220$ km s^{-1}) extending out to at least 100 kpc.

More elaborate studies which include the dynamics of the angular momentum of the Local Group and interactions with nearby galaxies give similar estimates for the total galactic mass: see for example Raychaudhury and Lynden-Bell (1989). Peebles (1990) modeled the formation of the Local Group and derived a total mass of about $2 \times 10^{12}\ M_\odot$ for the Galaxy. Kroeker and Carlberg (1991) checked the accuracy of the timing argument mass estimates by examining binary systems identified in $\Omega = 1$ CDM simulations. They find that timing arguments (assuming radial orbits) typically underestimate the total masses by a factor of about 1.7.

7. Summary

- The mass of the known luminous components of the Galaxy is in the range (5 to 12) $\times 10^{10}\ M_\odot$.
- From the rotation curve of the Galaxy, $M(20\ kpc) \approx 22 \times 10^{10}\ M_\odot$.
- The escape velocity at the solar radius, estimated from high velocity stars in the solar neighborhood, indicates that the galactic mass $> 30 \times 10^{10}\ M_\odot$.
- From the kinematics of distant stars and satellites, $M(50\ kpc) \approx 40 \times 10^{10}\ M_\odot$.
- The timing arguments from the radial velocities and distances of M31 and Leo I give a consistent asymptotic mass estimate M_{total} of at least $120 \times 10^{10}\ M_\odot$.

8. Conclusion

The data are consistent with a mass distribution $M(R) \approx R(kpc) \times 10^{10}$ $M_{\odot}$ (corresponding to a flat rotation curve with $V_c \approx 220$ km s^{-1}), extending out to $R \geq 100$ kpc. The inferred ratio of the mass of the dark corona to the mass of the visible components of the Galaxy is at least 10.

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