Chapter 13

Dark Matter in Elliptical Galaxies?

Dark matter in elliptical galaxies includes both central black holes and extended dark halos. On dimensional grounds, one might expect that the velocity dispersion profile $\sigma(r)$ of an elliptical galaxy to be related to the cumulative mass profile $M(r)$ by

$$M(r) \simeq \frac{r\,\sigma^2(r)}{G}\,. \tag{13.1}$$

In fact, dispersion alone does *not* provide enough information; without additional constraints on the velocity *anisotropy*, a very wide range of mass profiles are consistent with a given dispersion profile. Luckily, there is one component commonly found in elliptical galaxies which can be used to detect extended dark halos – X-ray emitting gas.

13.1 Jeans Models of Spherical Systems

Perhaps the simplest application of the Jeans equations is to equilibrium spherical systems. Assuming that all properties are constant in time and invariant with respect to rotation about the center, the radial Jeans equation is

$$\frac{d}{dr}(\nu\overline{v_r^2}) + \frac{2\nu}{r}(\overline{v_r^2} - \overline{v_t^2}) = -\nu\frac{d\Phi}{dr}\,, \tag{13.2}$$

where ν is the stellar density, and v_r and v_t are velocities in the radial and tangential directions, respectively. Define the radial and tangential dispersions,

$$\sigma_r^2 \equiv \overline{v_r^2}\,, \qquad \sigma_t^2 \equiv \overline{v_t^2}\,, \tag{13.3}$$

and the anisotropy,

$$\beta \equiv 1 - \sigma_t^2/\sigma_r^2\,, \tag{13.4}$$

which is $-\infty$ for a purely tangential velocity distribution, 0 for an isotropic distribution, and $+1$ for a purely radial velocity distribution. Then (13.2) becomes

$$\frac{1}{\nu}\frac{d}{dr}(\nu\sigma_r^2) + \frac{2}{r}\beta\sigma_r^2 = -\frac{d\Phi}{dr}\,. \tag{13.5}$$

If $\nu(r)$, $\beta(r)$, and $\Phi(r)$ are known functions, (13.5) may treated as a differential equation for the radial dispersion profile. Thus one application of this equation is making models of spherical systems. From an observational point of view, however, $\nu(r)$ and $\sigma_r(r)$ may be known, and the goal is to obtain the mass profile, $M(r)$. Using the relation

$$\frac{d\Phi}{dr} = G\frac{M(r)}{r^2}, \tag{13.6}$$

the mass profile is given by

$$M(r) = -\frac{\sigma_r^2 r}{G}\left(\frac{d\ln\nu}{d\ln r} + \frac{d\ln\sigma_r^2}{d\ln r} + 2\beta(r)\right). \tag{13.7}$$

The catch here is that we don't know $\beta(r)$. One option is to assume that the velocity distribution is isotropic, so that $\beta = 0$ for all r. This allows us to calculate mass profiles, but the results are uncertain because there is no good reason why velocity distributions should be isotropic. Another option is to assume that the galaxy has a constant mass-to-light ratio, and calculate the anisotropy profile $\beta(r)$ needed to satisfy (13.7) (Binney & Mamon 1982).

13.2 Black Holes

A central black hole of mass $M_\bullet$ exerts a strong influence on the dynamics of a system with velocity dispersion σ inside a radius $r_{\rm infl} \simeq GM_\bullet/\sigma^2$. This is a very small radius, typically of order $10^{-2}R_{\rm e}$ or less; thus high spatial resolution is required to clearly detect central black holes.

13.2.1 Case study: M87

Early studies of M87 (= NGC 4486) *assumed* an isotropic velocity distribution, and used measurements of surface brightness and line-of-sight velocity dispersion to try and measure the mass profile; the results suggested the presence of a large unseen mass – presumably a black hole – at small radii (Sargent et al. 1978). But Binney & Mamon (1982) showed that the observations could be fit by a radially anisotropic velocity distribution with no unseen mass of any kind. van der Marel (1994) reaffirmed this point by fitting the data with two kinds of models: anisotropic models with no black hole and isotropic models with a black hole.

Now that observations of a disk of ionized gas at the center of M87 have established the presence of a black hole of mass $M_\bullet \simeq 2.4\times10^9\,\mathrm{M}_\odot$ (Harms et al. 1994) one may turn the analysis around and try to estimate the degree of velocity anisotropy required. Dressler & Richstone (1990) and Merritt & Oh (1997) have shown that the relatively flat dispersion profile of M87 can be reconciled with a supermassive black hole if the velocity distribution is strongly biased in the *tangential* direction near the center of M87. Tangential velocity distributions are also reported in other well-studied galaxies with central black holes (eg., Gebhardt et al. 2007).

13.2.2 Case study: M32

The nearby dwarf elliptical galaxy M32 (= NGC 221) exhibits clear evidence of a central black hole. Tonry (1984) found a "central bump" in the velocity dispersion profile and an "unresolved jump" in the rotation curve at small radii; he noted that these features were consistent with a central dark object of $\sim 5\times10^6\,\mathrm{M}_\odot$. Subsequent studies with better data and modeling have reduced the black-hole mass by a factor of ~ 2, but strongly exclude solutions without a central black hole (see Kormendy 2004).

A more recent study by Verolme et al. (2002) illustrates the state of the art in black hole detection. Integral-field spectroscopy is used to measure the stellar line-of-sight velocity V, projected velocity dispersion σ, and line-shape parameters h_3 and h_4 across the face of the galaxy; these data are supplemented with HST spectroscopy. The observations are fit to an axisymmetric three-integral model using Schwarzschild's (1979) method; besides determining a black-hole mass of $(2.5 \pm 0.5) \times 10^6\,\mathrm{M}_\odot$, the fit also constrains the inclination ($70\,\mathrm{deg} \pm 5\,\mathrm{deg}$), intrinsic flattening (0.68 ± 0.03) and I-band mass-to-light ratio ($1.85 \pm 0.15\,\mathrm{M}_\odot/\mathrm{L}_\odot$).

This very well-constrained solution is possible thanks to several different factors. First M32 is nearby, so high spatial resolution is relatively easy to obtain. Second, the galaxy's rapid rotation strongly suggests that it is axisymmetric. Third, its steep luminosity profile provides high surface brightness at small radii and simplifies the relationship between projected and intrinsic kinematics.

13.3 Dark Halos

Dark halos are *more* extended than the stellar components of typical galaxies; to detect the dynamical effects of halos, we need to measure stellar kinematics at several R_e. This is difficult because the surface brightness becomes too low for absorption-line spectroscopy. One option is to use planetary nebulae (PN), which are easily detected in narrow-band imaging and can trace the stellar halos of galaxies to many R_e.

13.3.1 Case study: NGC 4697

Recently the kinematics of the E6 galaxy NGC 4697 have been probed out to $5R_\mathrm{e}$ by line-of-sight velocity measurements of 591 planetary nebulae (Méndez et al. 2001, 2009). The data show σ falling in a nearly Keplerian fashion, inviting the speculation that this galaxy has no dark halo. As an illustration, a spherical Hernquist (1993) model provides an excellent fit to the observed velocity dispersion profile, yielding a B-band mass-to-light ratio $M/L \simeq 9$ independent of radius. But this fit *assumes* that the PNs have isotropic velocities; is this assumption justified?

Reviewing similar data-sets for other galaxies, Romanowsky et al. (2003) suggested that elliptical galaxies do not have dark halos. This result would appear to be at odds with prevailing ideas on galaxy formation. However, velocity dispersion profiles don't tell the whole story; more information can be gleaned by examining velocities of individual PN. In NGC 4697, a small number of PNs have line-of-sight velocities uncomfortably close to the escape velocity for a no-halo model; unbound stars would leave the galaxy long before becoming planetary nebulae, so the actual escape velocity must be greater than implied by the no-halo model.

More comprehensive models suggest that NGC 4697 *does* have a dark halo. De Lorenzi et al. (2008) use an N-body method similar to Schwarzschild's technique to produce axisymmetric models both with and without dark halos. The mean velocity and velocity dispersion data can be fit quite well without a dark halo. But when individual PN velocities are added to the constraints, models without dark halos appear to be inconsistent with the data; the best-fitting models have significant radial anisotropy ($\beta \simeq 0.5$) at large radii.

13.3.2 Hydrostatic Equilibrium of Hot Gas

There is one galactic component which is *known* to possess an isotropic velocity distribution: the hot gas responsible for extended X-ray emission in ellipticals. In this case the observable quantities are the gas density and temperature profiles, $n_{\rm e}(r)$ and $T(r)$, respectively. In terms of these the mass profile is

$$M(r) = -\frac{kT(r)r}{Gm_{\rm p}\mu}\left(\frac{d\ln n_{\rm e}}{d\ln r} + \frac{d\ln T}{d\ln r}\right). \tag{13.8}$$

where k is Boltzmann's constant, $m_{\rm p}$ is the proton mass, and μ is the mean molecular weight (e.g. Sarazin 1987). The parallels between (13.7) and this equation are obvious.

This method has several advantages: (1) it requires no assumptions about velocity anisotropy, (2) it probes the mass distribution at radii where the stellar surface brightness is too low to measure velocity dispersions, and (3) with enough X-ray telescope time, good statistics can be accumulated, whereas tracers such as globular clusters and planetary nebulae are limited in number. But for a long time, very few galaxies were well enough resolved to yield detailed temperature profiles.

Recent *Chandra* and it XMM-Newton observations provide the sensitivity and spatial resolution to needed to unambiguously detect dark halos. For example, Humphrey et al. (2006) present results for seven luminous elliptical galaxies, all surrounded by relaxed, approximately spherical envelopes of hot, X-ray emitting gas. All seven have extensive halos of dark matter, with total masses an order of magnitude larger than the total stellar masses.

13.3.3 Case study: NGC 4472

X-ray data for NGC 4472 (Trinchieri et al. 1986; Irwin & Sarazin 1996) can be used to constrain the mass distribution of this galaxy (Lowenstein 1992; Mathews & Brighenti 2003). The gas has $T \simeq 10^7$ K and samples the potential out to nearly $10R_{\rm e}$. An analysis using (13.8) shows that a dark halo is clearly present beyond $\sim 1R_{\rm e}$ and may account for $\sim 90\%$ of the total mass within $10R_{\rm e}$. For an adopted blue mass-to-light ratio $M/L \simeq 7$, the stellar component dominates the mass at $0.1R_{\rm e}$; to account for the observed profile of velocity dispersion with radius, the stellar velocity distribution must be radially anisotropic, with $\beta \simeq 0.53$ out to nearly $1R_{\rm e}$.