DARK MATTER HALOS AROUND ELLIPTICAL GALAXIES: HOW RELIABLE IS THE STELLAR KINEMATICAL EVIDENCE?

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ABSTRACT

Hierarchical models of galaxy formation and various observational evidence suggest that elliptical galaxies are, like disk galaxies, embedded in massive dark matter halos. Stellar kinematics are considered the most important tracer for this dark halo at a few effective radii. Using detailed modeling techniques, several authors have recently presented stellar kinematical evidence of a dark halo for a number of elliptical galaxies. In these modeling techniques, dust attenuation (absorption and scattering of starlight by dust grains) has not been taken into account. Nevertheless, elliptical galaxies contain a significant amount of interstellar dust, which affects all observable quantities, including the observed kinematics. We constructed a set of dynamical models for elliptical galaxies, in which dust attenuation is included through a Monte Carlo technique. We find that a dust component, shallower than the stellar distribution and with an optical depth of order unity, affects the observed kinematics significantly, in the way that it mimics the presence of a dark halo. If such dust distributions are realistic in elliptical galaxies, we are faced with a new mass-dust degeneracy. Taking dust attenuation into account in dynamical modeling procedures will hence reduce or may even eliminate the need for a dark matter halo at a few effective radii.

Subject headings: dark matter — dust, extinction — galaxies: elliptical and lenticular, cD — galaxies: halos — galaxies: kinematics and dynamics

1. INTRODUCTION

It has been generally accepted for decades that disk galaxies are ubiquitously embedded in massive dark matter halos. During the past few years, a consensus has been developing that elliptical galaxies also contain dark halos. Their existence is predicted by hierarchical theories of galaxy formation and has recently been supported by various observational evidence, such as gravitational lensing (Griffiths et al. 1996; Keeton, Kochanek, & Falco 1998) and X-ray measurements of their hot gas atmospheres (Matsushita et al. 1998; Loewenstein & White 1999). Although useful to infer the large-scale mass distribution of elliptical galaxies, these observations do not sufficiently constrain the detailed structure of the mass distribution at a few effective radii. This region is particularly important for understanding the coupling of the dark and luminous matter. In order to constrain the gravitational potential at these radii, other, kinematical, tracers are used. For disk galaxies, the neutral hydrogen gas, which radiates at 21 cm, forms an excellent kinematical tracer; elliptical galaxies, however, usually lack the necessary amounts of interstellar gas. Discrete tracers such as planetary nebulae, globular clusters, and dwarf satellite galaxies can be used (Zepf et al. 2000; Romanowski & Kochanek 2001; Kronawitter et al. 2000), but due to their small numbers and larger distances to the center, they do not sufficiently constrain the gravitational potential at a few K. This leaves stars as the main tracers for the mass distribution in elliptical galaxies in this region.

The first stellar kinematical evidence for dark matter halos around elliptical galaxies came in the early 1990s. At that time, the available kinematical data consisted of the mean projected velocity \( \langle v_p \rangle \) and the projected velocity dispersion \( \sigma_p \) at projected radii rarely larger than 1K. For a number of elliptical galaxies, the projected velocity dispersion profile was found to decrease only slowly with projected radius, a behavior that was interpreted as a signature for the presence of a dark matter halo (Saglia, Bertin, & Stiavelli 1992; Saglia et al. 1993). However, such \( \sigma_p \) profiles can also be generated by intrinsically tangentially anisotropic galaxy models, without the need for dark matter halos. The velocity dispersion profile alone does not contain sufficient kinematic information to constrain both the mass and the orbital structure of elliptical galaxies, a problem usually referred to as the mass-anisotropy degeneracy (Gerhard 1993). This degeneracy can be broken by considering the higher order kinematical information contained in the line-of-sight velocity distributions (LOSVDs), usually parameterized by means of the Gauss-Hermite shape parameters \( h_i \) (where \( i \geq 3 \); Gerhard 1993; van der Marel & Franz 1993). In particular, the additional information contained in the \( h_4 \) profile provides the key to breaking the mass-anisotropy degeneracy: the combination of a slowly decreasing velocity dispersion profile together with a relatively large \( h_4 \) profile is generally interpreted as evidence of a dark matter halo.\(^2\) Thanks to improved instrumentation and data reduction techniques, it is nowadays possible to determine the \( \langle v_p \rangle \), \( \sigma_p \), \( h_3 \), and \( h_4 \) profiles with reasonable accuracy, out to several K. Several authors have recently adopted such kinematical information to constrain the dark matter distribution in a number of elliptical galaxies (Rix et al. 1997; Gerhard et al. 1998; Saglia et al. 2000; Kronawitter et al. 2000).

In this entire discussion, it has (implicitly) been assumed that elliptical galaxies consist of two dynamically important components: the stars moving as test particles in a gravitational potential, generated by both stellar and dark mass. During the past decade, it has become well established that elliptical galaxies also contain a surprisingly large amount of interstellar dust (up to several million solar masses), most of it believed

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\(^2\) For a detailed analysis of the effects of mass and anisotropy on the projected dispersion and \( h_4 \) profiles, we refer to § 3 of Gerhard et al. (1998).
to be distributed diffusely over the galaxy (Roberts et al. 1991; Goudfrooij & de Jong 1995; Bregman et al. 1998). This number must be revised an order of magnitude upward if more detailed dust mass estimators (Merluzzi 1998) or additional submillimeter measurements (Fich & Hodge 1993; Wiklind & Henkel 1995) are taken into account. This is still a negligible fraction of the total mass of the galaxy, such that the dust will hardly influence the gravitational potential. Nevertheless, it has a significant role in galaxy dynamics: dust grains efficiently absorb and scatter optical photons. Interstellar dust will therefore affect all observable quantities, including the observed kinematics.

We are undertaking an effort to understand the impact of interstellar dust on the observed kinematics in elliptical galaxies. Previously, we investigated how absorption by dust grains affects the light profile and the observed kinematics (Baes & Dejonghe 2000; Baes, Dejonghe, & De Rijcke 2000). We found that the observed kinematics are affected only in the most central regions, the magnitude of these effects being on the order of a few percent. Here we have extended our modeling to incorporate the process of scattering off dust grains. We will show in this Letter that this has a considerable effect on the observed kinematics, in particular concerning the stellar kinematical evidence of dark matter halos.

2. THE MODELING

To investigate the effects of attenuation on the observed kinematics, we constructed a spherically symmetric elliptical galaxy model, consisting of a stellar component and a dust component. For the stellar distribution, we adopted an isotropic Hernquist model. For the dust distribution, we adopted an elliptical model, consisting of a stellar component and a dust component. For the stellar distribution, we adopted an isotropic Hernquist model. For the dust distribution, we adopted an elliptical model, consisting of a stellar component and a dust component. For the stellar distribution, we adopted an isotropic Hernquist model. For the dust distribution, we adopted an elliptical model, consisting of a stellar component and a dust component. For the stellar distribution, we adopted an isotropic Hernquist model. For the dust distribution, we adopted an elliptical model, consisting of a stellar component and a dust component. 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high-velocity stars in the galaxy center are only slightly obscured. As a result, the velocity dispersion only decreases marginally. At large radii, however, the kinematics are seriously affected. The σ_p profile drops less steeply, and the h_4 parameter is significantly larger compared with the dust-free case. In Figure 2, we show the LOSVD at R = 5R_e of our galaxy model, with and without dust attenuation. This figure clearly indicates that dust attenuation brings on significant high-velocity wings in the outer LOSVDs. In particular, it should be noted that these LOSVDs do not vanish at the local escape velocity; hence, stars are observed that cannot physically be present on these lines of sight. These wings represent a scattering effect, as demonstrated in Figure 3, and they are responsible for the increase of σ_p and h_4. Attenuation by interstellar dust apparently has a kinematical signature that is strikingly similar to the presence of a dark matter halo: a velocity dispersion profile that decreases more slowly than expected and a relatively large h_4 profile. Hence, dust-affected kinematics mimic the presence of a dark matter halo.

4. MODELING THE DUST-AFFECTED KINEMATICS

To check this in more detail, we considered our dust-affected kinematics as an observational data set and modeled it as any dynamical modeler would do, i.e., without taking dust attenuation into account. We concentrated on the model with optical depth τ_v = 1 and considered a data set consisting of the K-band photometry and V-band σ_p and h_4 profiles, out to 5R_e. The modeling was performed with a powerful nonparametric modeling technique based on quadratic programing (Dejonghe 1989).

4.1. Models with a Constant M/L

First, we tried to find out whether or not the data were consistent with a model with a constant M/L. We constructed a set of dynamical models, with M/L as a free parameter. The best-fitting model is represented by the dashed line in Figure 4. Obviously, this fit is not satisfactory: it can fit the σ_p profile, but only through a strong tangential anisotropy, reflected in a strongly negative h_4 profile. It is impossible to fit both the σ_p and h_4 profiles with a constant M/L model.

4.2. Models with a Dark Matter Halo

In order to construct models with a rising M/L, i.e., with a dark halo, we considered a set of Hernquist potentials, each with a different scale length. We constructed a set of dynamical models, with both the potential scale length and the mass-to-light ratio as free parameters. The best fit to the photometry and the σ_p and h_4 profiles is plotted as solid lines in Figure 4. Its potential has a scale length 45% larger than the original Hernquist potential, and in the maximum stellar mass hypothesis (the analog of the maximum-disk hypothesis in disk galaxies), the dark matter contributes roughly a third of the total mass within 1R_e and half of the total mass within the last data point. This clearly

\[ \frac{M}{L} \]

\[ \frac{R}{M} \]

\[ \frac{V}{L} \]
demonstrates that the effects of dust attenuation can mimic the presence of a dark matter halo. Taking dust attenuation into account in dynamical modeling procedures will hence reduce or may even eliminate the need for a dark matter halo at a few $R_e$.

5. CONCLUSIONS

In view of these results, we may have to reconsider the stellar kinematical evidence of dark matter halos. In analogy with the mass-anisotropy degeneracy, which could be lifted by considering higher order shape parameters for the LOSVDs, we are now faced with a new degeneracy, which could be called the mass-dust degeneracy. Indeed, the attenuation (in particular the scattering) by dust grains has the same effect on the stellar kinematics as a dark matter halo. At the least, these results apply to the model that we have explored in this Letter, with a dust distribution shallower than the stars and with an optical depth $\tau = 1$. We are well aware that these assumptions are quite uncertain, and an extended set of models, with a large variety in optical depth and star-dust geometry, is being investigated.

The new mass-dust degeneracy strongly complicates the use of stellar kinematics as a tracer for the mass distribution in elliptical galaxies. Although the presence of dark matter halos nowadays seems firmly established at very large scales, this leaves us with a major problem concerning the determination of the dark halo properties at a few effective radii. There are two possible ways to break this new degeneracy. The first option is to observe the kinematics at near-infrared wavelengths, where the effects of dust are negligible. However, this poses a serious observational challenge in the off-center regions. The second option is to include radiative transfer calculations in dynamical modeling techniques. Besides being a computational challenge, this requires a better understanding of the spatial distribution and of the optical properties of dust grains in elliptical galaxies than we have today. The new generation of far-infrared and submillimeter instruments, such as ALMA and SIRTF, will help us to solve this problem.

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