A Search for Dark Matter in Elliptical Galaxies

G. BERTIN[1], F. BERTOLA[2], L. M. BUSON[3], I. J. DANZIGER[4], H. DEJONGHE[5], E. M. SADLER[6], R. P. SAGLIA[1], M. VIETRI[7], P. T. DE ZEEUW[8], W. W. ZEILINGER[2,]*

[1] Scuola Normale Superiore, Pisa, Italy; [2] Dipartimento di Astronomia, Padova, Italy; [3] Osservatorio Astronomico, Padova, Italy; [4] ESO; [5] Observatorium, R. U. G., Gent, Belgium; [6] Anglo-Australian Observatory, Epping, Australia; [7] Osservatorio Astronomico, Roma, Italy; [8] California Institute of Technology, Pasadena, USA

One of the most remarkable discoveries of recent years is that of the presence of extended dark massive halos around spiral galaxies (see e.g. Rubin 1986). For these galaxies, the overall mass distribution is inferred from rotation curves derived from both ionized gas and atomic hydrogen emission. The best evidence for dark matter comes from the fact that the rotation curves remain flat, well beyond the optical disk. This result implies that the mass-to-light ratio M/L increases outwards, indicating a substantial amount of dark matter at large radii. A well-known case is NGC 3198, where the observed H I rotation curve is flat out to 11 exponential scale lengths h; here even the conservative maximum-disk analysis requires a dark to luminous mass ratio $M_D/M_L \approx 0.8$ at R_{25} and $M_D/M_L \approx 3.9$ at the outer edge (R = 11 h) (van Albada et al. 1985). The cosmological consequences of this result have been widely discussed in the context of the problem of the "missing mass" in the universe.

To date, the evidence for dark matter in elliptical galaxies is fragmentary, and not nearly as compelling as it is for spiral galaxies. The reasons for this are twofold. Spiral galaxies are thought to be circular disks, so their intrinsic shape follows immediately from the apparent flattening on the plane of the sky. Furthermore, these galaxies contain large amounts of H I, which is an excellent kinematic tracer of the mass distribution. By contrast, elliptical galaxies are thought to be triaxial, which complicates the determination of the intrinsic shape considerably. Furthermore, only very few ellipticals with significant amounts of cold gas are known, and emission lines are generally inconspicuous. As a result, a number of studies have employed other kinematic tracers. X-ray emission has often been taken to indicate the presence of large amounts of dark matter around elliptical galaxies (e.g., Fabian et al. 1986), although this interpretation is still subject to discussion (Canizares, Fabbiano and Trinchieri 1987). Further evidence has been provided by Dressler (1979), who noted that in some cD galaxies the stellar velocity dispersion increases outwards, out to very low surface brightness levels ($\approx$24 mag arcsec^{-2} in B). The kinematics of the globular cluster system of M87 is consistent with an M/L that increases with radius (Mould, Oke and Nemec 1987). The same conclusion is reached for NGC 5128 (Cen A), on the basis of radial velocity measurements of planetary nebulae in the halo of this galaxy (Ford et al. 1989). The large intrinsic velocity dispersions of the above-mentioned kinematic tracers make it difficult to draw firm conclusions regarding the behaviour of M/L. It is therefore not surprising that perhaps the strongest indication for an increase of M/L outwards comes from the few cases where an H I disk with a flat rotation curve has been detected (e.g., Raimond et al. 1981), as well as from the recent observations of an H I ring around the elliptical galaxy IC 2006 (Schweizer, van Gorkom and Seitzer 1989).

The aim of our key project is to establish on firm grounds the mass distribution in elliptical galaxies. We plan to investigate the two-dimensional velocity fields of the gaseous disks seen in a number of ellipticals, as well as the behaviour of the stellar velocity dispersion profile out to large radii. The results are expected to have important consequences for our understanding of galactic structure and of the processes of galaxy formation. In addition, specific constraints on the distribution of dark matter are expected to bear on the problem of its composition and thus to have significant cosmological implications.

Ellipticals with Gas Disks

Disks of ionized gas have been detected in a number of elliptical galaxies. This material is thought to have been acquired from the outside (Bertola, Galletta and Zeilinger 1985; Bertola and Bettoni 1988; Bertola, Buson and Zeilinger 1988), and in many cases will have settled in one of a few possible preferred planes. If the galaxy is triaxial, and has a non-rotating figure, the gas settles in the plane perpendicular to the long axis of the system, or in the plane perpendicular to the short axis, and moves in orbits that are approximately elliptic, and are elongated along the minor or intermediate axis, respectively. If the galaxy has a rotating figure, the preferred planes generally do not coincide with the principal symmetry planes of the galaxy (Merritt and de Zeeuw, 1983; Steiman-Cameron and Durisen 1982, 1988).

In order to derive the mass distribution of the elliptical galaxy (and therefore the trend of M/L), one needs to determine the axial ratios of the galaxy and the angles θ and Φ giving its orientation with respect to the line of sight. These quantities can be evaluated by imposing the following observational constraints (de Zeeuw and Franx 1989): ellipticity ε of the stellar body (direct imaging), axial ratio of the gaseous disk (Hα imaging), angle between isophotal major axis and rotation axis of the gaseous disk (study of the two-dimensional gas velocity field) and position angle of the inner disk's major axis (Hα imaging).

Once the shape and the orientation of the galaxy has been determined it is possible to evaluate the deviations from circular motions introduced by a triaxial potential (Gerhard and Vietri 1986; de Zeeuw and Franx 1989). Bertola et al. (1989) have done this for the E3 galaxy NGC 5077, which has an emission line gas disk with measured gas velocities along 7 position angles. These authors show that the available data are consistent with a triaxial model with a constant M/L over the modest radial extent of the observations. In particular, the slow rise of the rotation curve in the inner parts of the galaxy is shown to be due to the specific orientation at which this galaxy is observed.

As part of the key project, we will apply this same analysis to a sample of elliptical galaxies, so that we cover a wide range of viewing angles θ and Φ,

* Affiliated to the Astrophysics Division of the Space Science Department of ESA

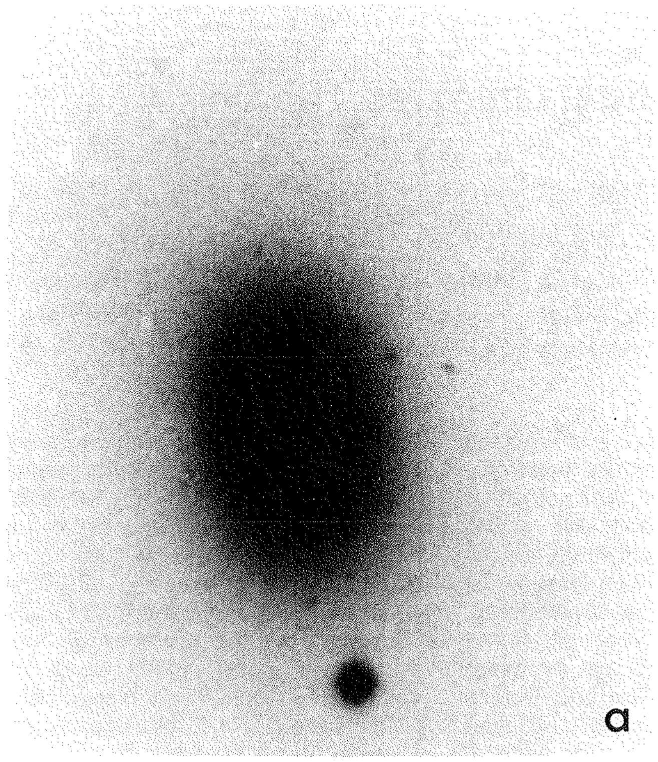

Figure 1 a: *A continuum image of the E galaxy NGC 5077, which reveals the distribution of the stellar component (N-top, E-left). A surrounding swarm of globular clusters is just visible.*

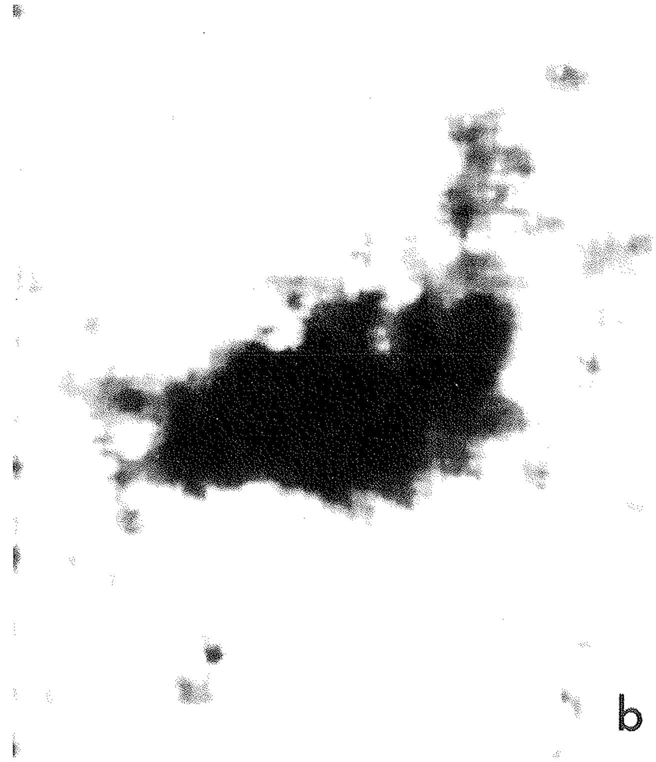

Figure 1 b: *An Hα image of NGC 5077 showing the tilted plane of the ionized gas with its apparent major axis lying almost orthogonal to the apparent major axis of the stars.*

and hence view the elliptic closed orbits at different angles.

Stellar Velocity Dispersions

Concentrated stellar dynamical models constructed under simple physical prescriptions turn out to be well fitted by an $R^{1/4}$ luminosity profile when a constant M/L ratio is assumed. One simple family of models (f_∞-models) has been tested in great detail on a survey of bright elliptical galaxies with available kinematical and photometric data (Bertin, Saglia and Stiavelli 1988a); it has been found to give excellent fits to the data and has provided (global) measurements of the M/L ratio, typically of order 10. These results tend to support the view that elliptical galaxies can effectively be described as one-component systems and that dark matter is either absent or distributed as the luminous matter. However, they rely on kinematical information that is quite restricted in radius or subject to sizeable errors. Therefore it is important to improve our knowledge of the kinematics of the stars in elliptical galaxies, and this can be done in three different ways:

(a) Measure the stellar velocity dispersion at $R \sim R_e$ with significantly reduced error bars;

(b) Extend the radial range ($R \sim 1-2\,R_e$) of the velocity dispersion profile;

(c) Extend the radial range ($R \sim 1-2\,R_e$) of the mean motion (rotation) data.

Evidently, these observations are not easy, and will require a substantial amount of telescope time.

Most likely such improved kinematical data will be in contrast with the expectations of the simple one-component models described above. If they turn out to be consistent with those expectations (i.e. low velocity dispersion and insignificant rotation) we may safely propose that in elliptical galaxies dark matter, if present, closely follows the distribution of the stars, at least out to the largest radius sampled by our kinematical data. Thus a "negative", result would actually offer the possibility to make a strong statement on the structure of ellipticals.

If rotation is found to be dynamically important in the outer parts, we would have to face the issue of constructing models that are "pressure" supported inside and "rotation" supported outside, in the presence of the ubiquitous $R^{1/4}$ profile. Very little has been done on this subject so far. These observations would stimulate interesting theoretical developments.

The second point of "failure" for the simple one-component models described above may derive from the velocity dispersion profile $\sigma(R)$ [see (a) and (b) above] which may be found to be flatter than expected. In this case we may have the best evidence of dark matter being distributed differently from the luminous matter. If we now assume that a dark component is indeed present, but with a more diffuse and extended density distribution than that of the luminous component, for a wide class of self-consistent models a relation can be obtained that gives the amount of dark matter enclosed in the sphere where kinematical information is available. This relation does not depend on the specific choice of distribution functions, provided pressure anisotropy is not unusual and mean motions of the stars are dynamically insignificant.

Since reasonable distribution functions have been found to have the $R^{1/4}$ law as a built-in property in the absence of dark matter, it would be important to show to what extent and under which conditions the presence of an "external field" due to dark matter can leave the luminosity profile *essentially unaltered;* this has been found to occur when the dark component is sufficiently diffuse (Bertin, Saglia and Stiavelli 1988b). Self-consistency is often responsible for subtle effects that go beyond the intuition provided by superposition. One thus has to develop a feeling for the mutual interactions of two spherical components by a direct (numerical) survey of a wide set of self-consistent two-component models (Saglia 1989). This study provides a valuable theoretical framework for the interpretation of the observational data that will be obtained on the basis of (a) and (b).

References

van Albada, T.S., Bahcall, J.N., Begeman, K., Sancisi, R., 1985: *Astroph. J.,* **295,** 305.
van Albada, T.S., Sancisi, R., 1986: *Phil. Trans. R. Soc.* London A **320,** 447.
Bertin, G., Saglia, R.P., Stiavelli, M., 1988a: *Astroph. J.,* **330,** 78.
Bertin, G., Saglia, R.P., Stiavelli, M., 1988b, in: *Astronomy, Cosmology and Fundamental Physics* (Proceedings of the Third ESO-CERN Symposium, Bologna, May 1988) Reidel Publ. Co., Dordrecht, Ed. G. Giacomelli.
Bertola, F., Bettoni, D., 1988: *Astrophys. J.,* **329,** 102.
Bertola, F., Bettoni, D., Danziger, I.J., Sadler, E.M., Sparke, L.S., de Zeeuw, P.T., 1989: *preprint.*
Bertola, F., Buson, L.M., Zeilinger, W.W., 1988: *Nature,* **335,** 705.
Bertola, F., Galletta, G., Zeilinger, W.W., 1985: *Astroph. J.,* **292,** L51.
Canizares, C., Fabbiano, G., Trinchieri, G., 1987: *Astroph. J.,* **312,** 503.
Dressler, A., 1979: *Astroph. J.,* **231,** 657.
Fabian, A.C., Thomas, P.A., Fall, S.M., White, R.E., 1986: *M.N.R.A.S.,* **221,** 1049.
Ford, H.C., Hui, X., Freeman, K.C., Dopita, M.A., Meatheringham, S.J., Ciardullo, R., Jacoby, G.H., 1989: *preprint.*
Gerhard, O.E., Vietri, M., 1986: *M.N.R.A.S.,* **223,** 377.
Merritt, D.R., de Zeeuw, P.T., 1983: *Astroph. J.* Letters, **267,** L23.
Mould, J.R., Oke, J.B., Nemec, J.M., 1987: *Astron. J.* **92,** 53.
Raimond, E., Faber, S.M., Gallagher III, S.J., Knapp, G.R., 1981: *Astrophys. J.,* **246,** 708.
Rubin, V.C., 1986, in: *Highlights of Astronomy* **7,** 27.
Saglia, R.P., 1989: *Ph. D. thesis,* in preparation.
Schweizer, F., van Gorkom, J.H., Seitzer, P., 1989: *Astroph. J.,* **338,** 770.
Steiman-Cameron, T.Y., Durisen, R.H., 1982: *Astrophys. J.,* **263,** L51.
Steiman-Cameron, T.Y., Durisen, R.H., 1988: *Astrophys. J.,* **325,** 26.
de Zeeuw, T., Franx, M., 1988: *Astrophys. J.,* submitted.

ESO'S EARLY HISTORY, 1953–1975

III. 26 May 1964: ESO Chooses La Silla*

A. BLAAUW, Kapteyn Laboratory, Groningen, the Netherlands

"Fehrenbach und ich haben den Eindruck, daß der Berg ein großer Glücksfall ist."
From a letter of O. Heckmann to J.H. Oort of April 21, 1964.

In the course of the year 1962, towards the end of the site testing in South Africa, ESO became actively interested in the possibilities offered by the Andes Mountains in South America. After several years of exploration from American side, the Andes had been opened up for astronomy.

Jürgen Stock's Early Explorations

Among the first who explored the Andes was G.P. Kuiper of the University of Chicago, who examined in March 1959 the area from Antofagasta southward, mostly from the air with the help of the U.S. Air Force [1]. But fully involved in the tests over the years was Jürgen Stock. Stock received his degree in astronomy with Heckmann at Hamburg, and had subsequently been associated with the Boyden Observatory in South Africa. Through his education as an astronomer, his knowledge of the Spanish language, and a sense for pioneering in the almost inaccessible Andes Mountains, Stock became the explorer par excellence for AURA's project. His remarkable reports on the early AURA activities should be read by everyone who wishes to get an idea of what it meant, to conquer the Andes for astronomy [2].

Stock organized in April 1959, as a member of the staff of the University of Texas, a site survey initiated by the Universities of Chile, Chicago and Texas [3]. This was initially meant only for finding a good site for a 150 cm telescope in the vicinity of Santiago, but the survey grew in importance when it appeared that outstanding conditions might be found farther northward. As a result of Kuiper's move to the University of Arizona in 1960, AURA, supported by NSF, took over the management of the "Chile Project" from the University of Chicago [4]. On November 23, 1962 the AURA Site Survey Team chose Cerro Tololo as the site for the Observatory, a decision ratified by the AURA Executive Committee on December 1, 1962.

For the measurement of image quality Stock used a criterion different from that applied by ESO. Instead of going by the appearance of the diffraction image as observed with the Danjon telescopes, image motion was used: the rapid, erratic displacement of the stellar image. In the earlier deliberations of ESO this method had been contemplated – Couder suggested it early in 1954 [5] – but not chosen because it required much higher stability of the telescope mounting. Stock used a double beam telescope which measured the relative motion of images in the superimposed fields of two telescopes fixed on one mounting, of 10 cm aperture and 165 cm beam separation [6].

ESO's Growing Interest in the Andes

News on the promising results of the American tests reached European astronomers, first bit by bit, then more impressively. The minutes of the May 1959 meeting of the ESO Committee, referring to the work in the Santiago area still read: *"This project will have little influence on the development of ESO."* But soon after, interest grew rapidly, and the June 1961 meeting decided to send an experienced ESO observer to Chile with one of the Danjon telescopes used in South Africa.

Naturally, the possibility of finding a site better than those considered so far in South Africa, was exciting news. But there was also something else: a certain apprehension about South Africa's future due to the growing unrest in this country. Thus, a letter of April 1960 by Danjon to Oort contains this paragraph: *"Il règne une certaine inquiétude en France au sujet de l'Afrique du Sud, mais je m'efforce de la conjurer en expliquant que le projet ESO n'est pas nécessairement lié à l'Afrique – – –"*, and in his reply of May 10, 1960, Oort writes *"En vue des difficultés que vous signalez pour la France, difficultés qui existeront aussi dans d'autres pays, et en vue du fait que les Américains ont récemment obtenu des indications favorables pour les emplacements dans*

* Articles I and II appeared in *Messenger* **54** (December 1988) and **55** (March 1989).