THE ASTROPHYSICAL JOURNAL, 228:L1–L4, 1979 February 15

MEMBERSHIP AND VELOCITY DISTRIBUTION IN THE CORE OF THE VIRGO CLUSTER

G. HELOU AND E. E. SALPETER
Center for Radiophysics and Space Research, Cornell University

AND

N. KRUMM
Lick Observatory, University of California, Santa Cruz
Received 1978 July 17; accepted 1978 November 14

ABSTRACT

The question has been raised of whether some bright spirals with negative velocities and large angular diameters are true members of the Virgo cluster core or close foreground objects. We have observed 21 cm spectral profiles for seven of the negative-velocity galaxies. Using the Fisher-Tully method (correlation between luminosity and velocity width), we show that these galaxies are at the distance of the Virgo cluster and tend to have large masses. Spirals in the Virgo cluster core have a mean velocity similar to that of the ellipticals and lenticulars but a larger velocity dispersion (about the cluster mean). We conjecture that low-velocity spirals may have been converted into some form of lenticulars by tidal stripping of their outer disks.
Subject headings: galaxies: clusters of — radio sources: 21 cm radiation

I. INTRODUCTION

The possibility of a significant difference in mean velocity between the spiral and elliptical (and S0) galaxies in the Virgo I cluster was raised by de Vaucouleurs (1961). New redshift data have been added (de Vaucouleurs and de Vaucouleurs 1973; Sandage and Tammann 1976*a*) for the cluster core (of diameter ~12°). Controversy still remains, centered mainly on eight galaxies with negative (or very small positive) velocities, of which seven are spirals. Sulentic (1977) pointed out that five of these have a particularly large angular diameter, so they are either (*a*) bright, massive members of the cluster core, or (*b*) a small group of foreground galaxies. The accurate coincidence in angular position required for (*b*) is somewhat improbable, but in this case the galaxy group also would have to be much closer than the Virgo cluster—by more than 3.6 mag in the distance modulus, since the mean recession velocity would have to be less than about +200 km s^{-1} to produce so large a proportion of negative velocities (the M81 group at +240 km s^{-1} has *no* negative velocities). A measurement of the 21 cm velocity width of a spiral galaxy and of its apparent magnitude (Tully and Fisher 1977) can give its distance modulus to better than the minimum difference between (*a*) and (*b*). Burbidge and Hodge (1971) used an optical equivalent of this method (based on velocity gradients) to suggest cluster membership for NGC 4569. We have measured velocity widths with the 21 cm Arecibo[1] beam for seven of these galaxies and find that they are indeed at the distance of the Virgo cluster (to the required accuracy).

[1] The Arecibo Observatory is part of the National Astronomy and Ionosphere Center, which is operated by Cornell University under contract with the National Science Foundation.

With the negative-velocity spirals established as bright, massive members of the Virgo cluster, there is no significant spiral-elliptical difference in mean velocity. The membership of these galaxies confirms the fact (suggested by many authors) that spirals in the inner core of the Virgo cluster have a larger velocity dispersion than ellipticals and an "almost bimodal" velocity distribution. An expanding (Sulentic 1977) or collapsing (Moss and Dickens 1977) shell is one possible cause. In § III we speculate on another possibility: tidal interactions might preferentially mutilate the disks of spiral galaxies with lower velocities.

II. OBSERVATIONAL RESULTS

Figure 1 shows the distribution of all spiral galaxies (Sa or later) in the core of the Virgo cluster, defined by Sandage and Tammann (1976*a*) as a circle of 6° radius centered on 12^h25^m, + 13°06′ (1950), with $m_v < 14.5$ and velocities given either in de Vaucouleurs, de Vaucouleurs, and Corwin (1976, hereafter 2RCBG) or in Sandage and Tammann's list. With all systemic velocities V_s in the Local Group (LG) frame as given by Yahil, Tammann, and Sandage (1977), the center-of-mass velocity of the whole Virgo cluster is $V_{CM} \approx +1050$ km s^{-1}. For six of the seven spirals (plus one S0 pec) with "negative velocity" (defined as $V_s < +50$ km s^{-1}), we now have 21 cm data from the Arecibo Observatory.

We obtained spectral profiles for these seven galaxies (listed in Table 1) for the center of the galaxy and at least at ±2′ along the major axis (as given by Nilson 1973). The systemic velocity V and the "observed velocity width" ΔV in Table 1 are from the 21 cm data (ΔV is the velocity separation of the outer 35% points from a pair of off-center Arecibo profiles, which cor-

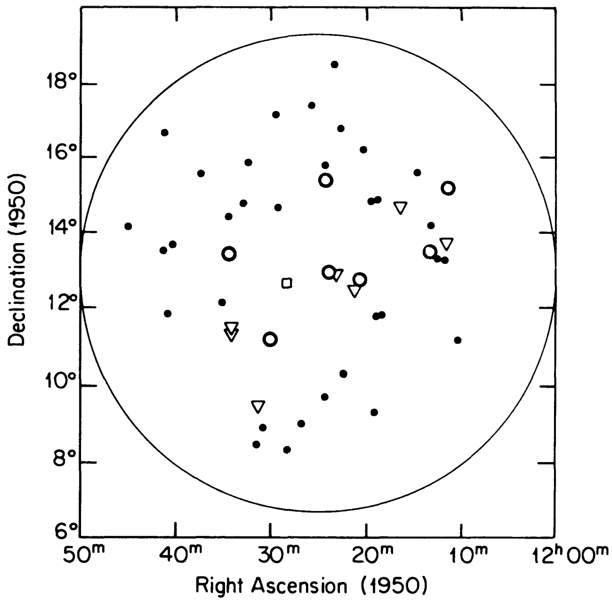

FIG. 1.—Distribution of spiral galaxies in the core of the Virgo cluster. *Large, open circles*, galaxies with $V_s < 50$ km s^{-1}; *points*, those with 50 km s^{-1} $< V_s <$ 2050 km s^{-1}; *triangles*, those with 2050 km s^{-1} $< V_s$. M87 is denoted by a square.

respond roughly to the 20% points on a "whole galaxy" profile). The optical radius R^* and blue apparent magnitude B^*, including a *partial* extinction correction, are defined as $R^* = 0.5[D_{25}D(0)]^{1/2}$ and $B^* = 0.5\,(B_T + B_T{}^0)$ with all quantities from 2RCBG. The inclination-corrected "full velocity width" ΔV_0 is defined as ΔV cosec i^*, with i^*, the galaxy inclination (relative to face-on), derived from the axis ratio R_{25} in 2RCBG by means of

$$\cos i^* = (R_{25})^{-1} - 0.05(\pm 0.05)\,. \qquad (1)$$

The term -0.05 is an empirical addition, designed to suppress unreasonably large values of ΔV_0 for small i^* but not very important for $i^* \gtrsim 50°$. In Figures 2 and 3 we plot B^* and R^* against ΔV_0, with the horizontal error bar representing the maximum possible error, incorporating ambiguity and measuring errors in ΔV, and the (± 0.05) in equation (1). For each of the six galaxies with $V_s < 50$ km s^{-1} and $i^* > 50°$, this maximum possible error is well known, and completely contained within the error bar.

As calibrators for the Virgo cluster, we use all galaxies within 9° of the center, with $+50$ km s^{-1} $< V_s <$ 2050 km s^{-1} and with $i^* > 30°$. Fisher-Tully data are now available for 21 of these galaxies, mainly from Tully and Fisher (1977), Sandage and Tammann (1976*b*), and Fisher and Tully (1977), but including six early-type disk galaxies (Krumm and Salpeter 1979). These 21 galaxies (with ΔV_0 defined as for the galaxies in Table 1) are also plotted in Figures 2 and 3 (without the error bars). The lower pair of dashed lines denote a band containing about two-thirds of these calibration galaxies (the subgroup with $i^* > 50°$ has a slightly smaller scatter but no strong displacement). Roberts (1978) and Rubin, Ford, and Thonnard (1978) have pointed out difficulties in finding a single "best-fit line" in the (B^*, ΔV_0)-relation, especially if selection criteria for brightness, inclination angle, and Hubble type are varied. However, the "two-thirds band" (instead of a "line") is sufficient for a comparison with our six negative-velocity galaxies with $i^* > 50°$ and with a similar range of apparent magnitudes and of Hubble types (mainly Sa to Sc) as the calibration galaxies.

The six heavy circles in Figure 2 are compatible with the Virgo band within the statistics; i.e., only two of the six (NGC 4438 and 4569) lie above the band. The deviation from the band for these two galaxies is appreciable but no greater than for the southern extension galaxy NGC 4517, for instance, which is thought

TABLE 1

SYSTEMIC VELOCITY V_s, APPARENT MAGNITUDE B^*, OPTICAL ANGULAR RADIUS R^*, OBSERVED VELOCITY WIDTH ΔV, AND CORRECTED VELOCITY WIDTH ΔV_0 FOR 12 GALAXIES

N(GC) or I(C) Number	Hubble Type	V_s (km s^{-1})	B^*	i^* (degrees)	ΔV (km s^{-1})	ΔV_0 (km s^{-1})	R^* (arcmin)
N4192..........	SAB(s)ab	−248	10.60	74	470	490	4.2
N4216..........	SAB(s)b	+17	10.58	78	524	535	3.5
N4413†.........	SB(rs)bP	(−79)	13.44	51	154–234	188–315	1.2
N4419†.........	SB(s)a	(−68)	11.68	71	239–396	245–430	1.5
N4438..........	SA(s)0/aP	−77	10.62	68	360	385	4.2
N4569..........	SAB(rs)ab	−356	10.01	64	348	368	4.4
I3258‡..........	SB(s)mP	−555	∼14.2	(33)	104	(193)	0.80
N4254§.........	SA(s)c	+2359	10.3	33	283	524	2.7
N4351‡.........	SB(rs)abP	+2201	12.36	49	114	(151)	0.98
N4388..........	SA(s)b	+2393	11.5	77	393	403	2.2
N4522‖........	SB(s)cd	+2184	13.3	75	228	236	1.6
N4517..........	SA(s)cd:sp	951	10.7	82	318	321	4.2

† The range in ΔV contains the maximum possible ambiguity due to superposed galactic emission.

‡ Mapping along the major axis shows no clear evidence of a velocity gradient or of extended emission; the relation between ΔV_0 and the rotational velocity is therefore uncertain. Errors in ΔV (if not in parentheses) are $\sim\pm 20$.

§ From Davies and Lewis 1973.

‖ From Huchtmeier, Tammann, and Wendker 1976.

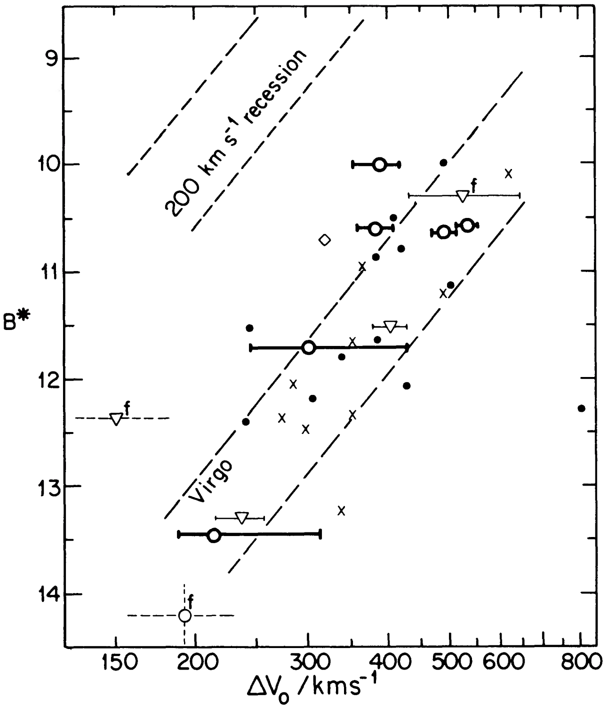

FIG. 2.—The apparent blue magnitude B^* plotted against the inclination-corrected velocity width ΔV_0. *Open circles*, galaxies with $V_s < 50$ km s^{-1}; *triangles*, those with 2050 km s$^{-1} < V_s$ (those with $i^* < 50°$ are marked by f); calibration galaxies are denoted by crosses for $i^* > 50°$ and points for $i^* < 50°$. The "recession" band is displaced from the "normal" Virgo band for a distance modulus change of 3.6 mag. Error bars cover completely ambiguity and measuring errors. The two dashed error bars refer to galaxies where the emission may not be extended and ΔV_0 may not be reliable. The diamond refers to the southern extension galaxy NGC 4517 with $V_s \approx 951$ km s^{-1}.

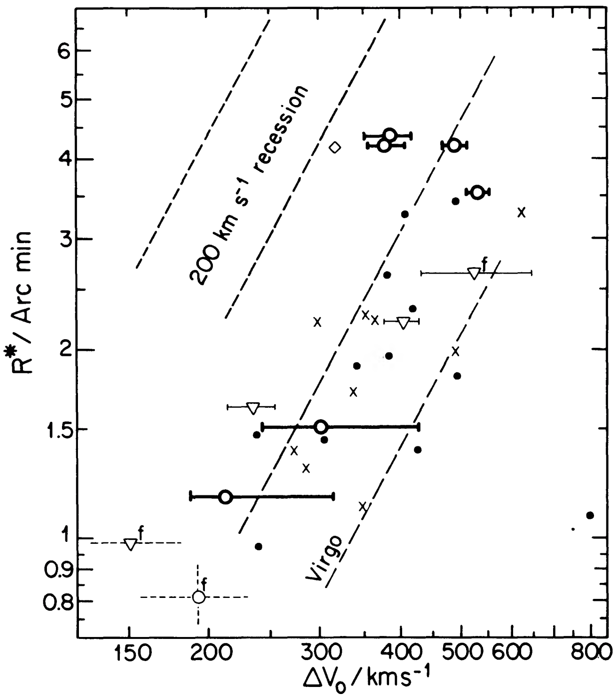

FIG. 3.—Same as Fig. 2 but with optical angular radius R^* plotted instead of B^*.

to be at the mean Virgo distance or even slightly *beyond*. The discrepancy with the Virgo band appears slightly worse on Figure 3, but the scatter is generally larger there (compare again NGC 4517). On the other hand, the six galaxies are *badly* discrepant with the "foreground hypothesis": as mentioned above, any foreground group close enough to include negative velocities should have a mean recession velocity $\ll$200 km s^{-1} and should lie *above* the upper pair of dashed lines in Figures 2 and 3. In reality, *all* six negative-velocity circles lie *below* this upper band (four of them, far below). We consider this as confirmation of the membership in the core of the Virgo cluster for these negative-velocity galaxies. We also note a trend toward large values of gravitational mass M, since $M \propto (\Delta V_0)^2 R^*$.

Table 1 also lists four galaxies in the Virgo cluster core with high velocities, $V_s > 2050$ km s^{-1}, but only two of them with $i^* > 50°$. These galaxies are also compatible with the Virgo band in Figures 2 and 3, although the statistics are poor. In any case, cluster membership for these galaxies has generally not been disputed.

III. DISCUSSION

The mass M of a galaxy is of the order of $G^{-1}(\Delta V_0)^2 R^*$. As mentioned, this combination is fairly large for a number of the negative-velocity galaxies and (to a lesser extent) those with high velocity. Although few in number, these galaxies therefore contribute significantly to the center-of-mass velocity $V_{\rm CM} = \Sigma M V_s / \Sigma M$ and even more to the velocity dispersion $\sigma^2 = \Sigma M(V_s - V_{\rm CM})^2/\Sigma M$. In the absence of precise masses we cannot evaluate these quantities accurately, but the inclusion of the negative-velocity galaxies (which are mainly spirals) lowers $V_{\rm CM}$ and raises σ for the spirals. The quantity σ is then significantly larger for the spirals than for the ellipticals and lenticulars (see Sandage and Tammann 1976*a*; Sulentic 1977; van den Bergh 1977), but there is no significant difference in $V_{\rm CM}$ between the two groups (because of the large σ and of "subclustering," differences less than ~100 km s^{-1} would not in any case be physically significant).

A comparison of our Figure 1 and Figure 1 in Sandage and Tammann (1976*a*) shows that (*a*) for velocities 50 km s$^{-1} < V_s <$ 2050 km s^{-1} the spirals (relative to the lenticulars) tend to avoid the inner part of the core (as is usual for denser clusters), whereas (*b*) for the high-dispersion velocities outside this range the spirals are concentrated in a band in the inner core. Spirals in the inner core of the Virgo cluster not only have a numerically large velocity dispersion but also have an "almost bimodal distribution of radial velocities," suggestive of a "hollow shell in three-dimensional velocity space." Moss and Dickens (1977) have observed a similar phenomenon in some other clusters of relatively low density. They have suggested spatially expanding or collapsing shells as one possibility, but we consider as another possibility selection effects amongst *bound* orbits (which require a core mass of order $5 \times 10^{14}\ M_{\odot}$).

Although "true" S0 galaxies are likely to be of a different nature, interactions in a cluster core may mutilate some spirals into forms which might be classified as "lenticular." The production of an "anemic" galaxy (van den Bergh 1976) by gas stripping through ram pressure from distributed gas in a cluster core is one example. Ram pressure increases with velocity (relative to V_{CM}), but tidal encounters are stronger for a spiral galaxy of *low* velocity and low mass and may strip the outer disk, decrease the disk luminosity, and "puff up" the remaining inner disk (Marchant and Shapiro 1977). We therefore conjecture that some fainter galaxies in the Virgo core with low velocity (relative to V_{CM}), which are classified as S0, are such "missing spirals." Photometry to faint magnitudes would be useful, since nuclei typical of spirals plus puffed-up, truncated disks are predicted.

This work was supported in part by NSF grant AST75-21153 and by the A. F. Morrison Memorial Research Fund. We are grateful to Drs. J. Binney, D. Burstein, S. Faber, W. Matthews, V. Rubin, S. van den Bergh, and G. de Vaucouleurs. We are especially indebted to M. Roberts for detailed advice and to A. Sandage and G. Tammann for unpublished data.

REFERENCES

Burbidge, E. M., and Hodge, P. M. 1971, *Ap. J.*, **166**, 1.
Davies, R., and Lewis, B. 1973, *M.N.R.A.S.*, **165**, 231.
de Vaucouleurs, G. 1961, *Ap. J. Suppl.*, **6**, 213.
de Vaucouleurs, G., and de Vaucouleurs, A. 1973, *Astro. Ap.*, **28**, 109.
de Vaucouleurs, G., de Vaucouleurs, A., and Corwin, H. 1976, *Second Reference Catalogue of Bright Galaxies* (Austin: University of Texas Press) (2RCBG).
Fisher, J. R., and Tully, R. B. 1977, *Comments Ap.*, **7**, 85.
Huchtmeier, W. K., Tammann, G. A., and Wendker, H. J. 1976, *Astr. Ap.*, **46**, 381
Krumm, N., and Salpeter, E. E. 1979, *Ap. J.*, **228**, in press.
Marchant, A. B., and Shapiro, S. L. 1977, *Ap. J.*, **215**, 1.
Moss, C., and Dickens, R. J. 1977, *M.N.R.A.S.*, **178**, 701.
Nilson, P. 1973, *Uppsala General Catalogue of Galaxies, Nova Acta*, Ser. 5:A, Vol. **1**.
Roberts, M. 1978, *A.J.*, **83**, 1026.
Rubin, V. C., Ford, W. K., and Thonnard, N. 1978, *Ap. J.* (*Letters*), **225**, L107.
Sandage, A., and Tammann, G. A. 1976*a*, *Ap. J.* (*Letters*), **207**, L1.
———. 1976*b*, *Ap. J.*, **210**, 7.
Sulentic, J. W. 1977, *Ap. J.* (*Letters*), **211**, L59.
Tully, R. B., and Fisher, J. R. 1977, *Astr. Ap.*, **54**, 661.
van den Bergh, S. 1976, *Ap. J.*, **206**, 883.
———. 1977, in *Vistas in Astronomy*, Vol. **21**, p. 71.
Yahil, A., Tammann, G. A., and Sandage, A. 1977, *Ap. J.*, **217**, 903.

George Helou: Cornell University, 326 Space Sciences Bldg., Ithaca, NY 14853

Nathan A. Krumm: Board of Studies in Astronomy and Astrophysics, Lick Observatory, University of California, Santa Cruz, CA 95064

Edwin E. Salpeter: Cornell University, 226 Space Sciences Bldg., Ithaca, NY 14853