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THE VELOCITY-DISTANCE RELATION FOR BRIGHT GALAXIES

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1. Introduction

The apparent distribution of bright galaxies (m < 15) is strongly anisotropic and indicates that the Local Group is an outlying clump of a large flattened cloud or supercluster of galaxies whose center is in the general direction of the Virgo Cluster(s) (Holmberg 1937, Reiz 1941, de Vaucouleurs 1953, 1956, 1959). The flattening of the system suggested that it might be rotating. An analysis of radial velocities available in 1956 disclosed departures from linearity and isotropy in the velocity-magnitude relation which could be interpreted by a simple kinematical model in a state of differential expansion and differential rotation (de Vaucouleurs 1958, 1959). The hypothesis was examined critically by van Albada (1962) who pointed out that systematic errors may be introduced by the spread of the luminosity function of galaxies and, in particular, that the observed non-linearity and anisotropy might reflect systematic variations depending on direction of the mean absolute magnitude of galaxies having a given type and apparent magnitude.

These problems will presently be re-examined in the light of additional magnitude and velocity data, including the southern hemisphere (G. and A. de Vaucouleurs 1964), and with the help of the independent absolute luminosity criteria developed by van den Bergh (1960). The system of supergalactic coordinates L, B previously defined (de Vaucouleurs 1956, 1958) will be used throughout.

The initial study (1958) was based on about 300 velocities of galaxies brighter than $m_{pg} \approx 14$ and within $|B| < 30°$; no velocity was available in the longitude range $150° < L < 260°$ corresponding to the southern sky. For the present study nearly 750 velocities of galaxies brighter than $m \approx 15$ are now available, including about 40 in the previously unobserved part of the southern sky; and regions of high latitude $|B| > 30°$ will be considered for comparison.

2. Spirals with a DDO Luminosity Classification

Luminosity estimates $\mathcal{L}$ based only on morphological criteria and presumed independent of apparent magnitude and red-shift are given by van den Bergh (1960) for 436 spiral galaxies north of $\delta = -28°$.

The DDO Catalogue of 436 spirals was used

a) to test van Albada's suggestion that the mean luminosity $\bar{\mathcal{L}}$ may depend on direction, especially on supergalactic longitude L,

b) to derive the velocity-magnitude relations in different directions with allowance for individual luminosities $\mathcal{L}$,

c) to derive the velocity-distance relation in different directions using van den Bergh's estimates of distance moduli.

Details of this investigation will be published elsewhere (de Vaucouleurs 1964); a summary of the main results follows:

If $\mathcal{L}$ = 1, 2, 3, ... 9 for DDO classes I, I-II, II, ..., V and if m_c is the B magnitude corrected for galactic absorption, then a least squares fit through the relation

(1) $$\log V_o = \text{cont.} + 0.2\ (1 + \mu)\ m_c - 0.1\ (1 + \lambda)\ \mathcal{L}$$

gives for 231 galaxies ($8 < m_c < 14$) $\mu = +0.048 \pm 0.047$ (m.e.) and $\lambda = -0.029 \pm 0.050$, i.e. a negligible correction to the provisional calibration $\Delta M / \Delta \mathcal{L} = 0.50$ (de Vaucouleurs 1962) and in the mean (over a large area of the sky) a negligible departure from the theoretical slope of the V/m/relation. Other tests show that the $\mathcal{L}$ estimates are essentially free of systematic errors depending on declination, galactic latitude and apparent magnitude).

A detailed analysis of the mean luminosity $\overline{\mathcal{L}}$ in different areas of the sky shows that regional variations are not significantly greater than could be expected from fluctuations in small samples, except possibly in one sector of the equatorial belt ($|B| < 30°$, $120° < L < 180°$) where spirals tend to be fainter than average by 0.4 mag. and in high latitudes ($B > +30°$) in the northern galactic hemisphere ($0° < L < 180°$) where spirals are about 0.6 mag. brighter than average. All other departures are within $\pm$ 0.2 mag. and the frequency distribution of the normalized residuals $\rho = (\overline{\mathcal{L}} - \overline{\overline{\mathcal{L}}})/\sigma$ in intervals of ρ = 0-1, 1-2, 2-3 for 15 regions is $N(\rho)$ = 7:6:2 which is close to the expected relative frequencies (3:2:1) for random samples from a normal distribution. There is, therefore, no statistical evidence in support of the van Albada's suggestion (a).

Further, the slight variations of $\overline{\mathcal{L}}$ in different sectors of the supergalactic equatorial belt even if taken at face value are not of the right sign and amplitude to account for the observed systematic variation of $\overline{V}(m)$ as a function of L.

In each magnitude interval the observed velocities V_o may be corrected for apparent and absolute luminosity on the assumption that $V = Hr$ over a small range of distances. If, then, a corrected velocity is defined by

$$(2) \quad \log V_c = \log V_o - \log \frac{r}{\overline{r}} = \log V_o + 0.1\,(\mathcal{L} - \overline{\overline{\mathcal{L}}}) - 0.2(m - \overline{\overline{m}})$$

the scatter of individual values is significantly reduced (from about 0.20 in $\log V_o$ to 0.13 in $\log V_c$), but the mean corrected velocities still depend on L in the equatorial belt and remain from 30 to 50 per cent greater near the south galactic pole than near the north galactic pole.

For example, a forced fit of the data in four broad sectors by a linear relation of the form

$$(3) \qquad \log V_c' = \log V_o + 0.1\,(\mathcal{L} - \overline{\overline{\mathcal{L}}}) = \alpha + \beta\,(m_c - 11.5)$$

gives the following coefficients:

Sector	$\|B\| < 30°$			$\|B\| > 30°$		
	α	β	n	α	β	n
$0° < L < 180°$ (N.G.H.)	3.054 $\pm$.010	0.201 $\pm$.011	128 m.e.	3.078 $\pm$.024	0.191 $\pm$.030	24 m.e.
$180° < L < 360°$ (S.G.H.)	3.104 $\pm$.015	0.227 $\pm$.021	32 m.e.	3.134 $\pm$.023	0.212 $\pm$.027	20 m.e.

In other words at m_c = 11.5 the mean velocity of spirals corrected for luminosity effects varies from +1132 $\pm$ 26 km/sec in the northern equatorial belt to +1360 $\pm$ 40 in the southern polar cap. Even though it is considerably reduced by the large areas of the sectors and the forced fit of a linear law, the systematic difference between different directions persists with a significant amplitude.

Finally, consider spirals in the supergalactic equatorial belt and which have a computed distance-modulus $30.0 \leq m_o - M(\mathcal{L}) \leq 30.9$ after van den Bergh; their mean velocities are as follows:

L	25	50	60	80	90	100	110	120	130	275	300	335	all
$\bar{V}_o$	+1537	+1053	+1242	+1186	+1009	+1396	+1370	+1183		+1785	+1300		+1280
n	9	9	9	11	9	9(*)	8	3		4	4		75

(*) including 7 in Virgo Cluster

Hence even when spirals in a small range of photometric distances (corrected for absolute luminosity) are selected the mean velocities are still 30 to 50 per cent higher in the anti-center sector.

The main conclusion is that if van den Bergh's estimates are reliable van Albada's suggestion is not substantiated, i.e. luminosity effects do not account for the major departures from a linear and isotropic velocity-distance relation.

3. Mean Velocities of Galaxies of all Types

The sample of spirals with DDO luminosity classes is small and does not include the important southern sky sectors where above average velocities were predicted by the kinematical model. A more complete analysis can be based on the 749 galaxies of known type which have both a B system magnitude and a velocity in the "Reference Catalogue".

Fig. 1 illustrates the distribution of V_o vs. L in the equatorial belt for elliptical and lenticular galaxies in several magnitude intervals. No corrections were applied for either absolute luminosity or galactic absorption. Similar results obtain for other types (details will be published elsewhere). Most show again a systematic variation of $\overline{V_o}$ with supergalactic longitude L in the equatorial belt ($|B| < 30°$). Removing the Virgo cluster

$(100° < L < 110°, -10° < B < 0°)$ does not alter significantly the results. No such effects are clearly present in the polar caps $(|B| > 30°)$. These results confirm the initial investigation and strengthen the evidence for a strong anisotropy in the velocity-distance relation in our neighborhood. Note especially that the new velocities in the southern sky $200° < L < 270°$ tend to be high, in agreement with the prediction of the kinematical model. The phenomenon is especially clear when mean velocities $\overline{V_o}$ are plotted vs. L in polar coordinates as in Fig. 2a and 2b. In these figures mean for points for all types from E to Sc were combined since differences in mean absolute magnitudes are negligible (de Vaucouleurs 1958); late-type system Sd to Im which are systematically fainter were excluded. In latitudes $|B| > 30°$, $\overline{V_o}(m)$ is roughly isotropic and an approximation to a linear Hubble's law obtains; not so in latitudes $|B| < 30°$ where conspicuous departures from linearity and isotropy are present.

4. Derivation of the Hubble Constant

Whatever the interpretation of the phenomenon, one consequence is of importance to cosmology, namely that the value of the Hubble constant derived from the velocity and distance of the Virgo cluster, or from nearby groups in the northern sky, is not a reliable estimate of the expansion parameter applicable to the law of red shifts in other directions of the sky or at greater distances. The situation is further complicated by the probable existence of two separate clusters in the Virgo area, the E-cloud and the S-cloud, having different mean velocities ($\overline{V_E} = 935 \pm 70$, $\overline{V_s} = 1409 \pm 166$) and presumably different distances (de Vaucouleurs 1961).

Thus if it were assumed that elliptical and lenticular galaxies (E, L) of apparent magnitude $11 < m < 12$ have a mean absolute magnitude of, say, $\overline{M_m}(E) = -18.5$, the derived value of the Hubble "constant" could range, according to the region selected for calibration, all the way from H = 84 km sec^{-1} Mpc^{-1} (7 galaxies with $|B| < 30°$ in the sector $70° < L < 100°$) to H = 168 (5 galaxies with $|B| < 30°$, and $250° < L < 310°$). Spirals of types S0/a to Sc (S0 - S5) give similar results; if $\overline{M_m}(S) = -18.5$ for $11 < m < 12$, then the range is from H = 98 (15 galaxies with $|B| < 30°$ and $80° < L < 110°$), to H = 191 (18 galaxies in $260° < L < 320°$). In order to remove this effect by the ad hoc assumption of anisotropy in $\overline{M_m}$ one would have to claim that galaxies of a given type and apparent magnitude have absolute luminosities that are systematically brighter by up to 1.5 magnitude in the southern sector. This is equivalent to 3$\mathcal{L}$ steps in the DDO luminosity scale and the presence of such large local variations is denied by van den Bergh's data. Nevertheless if, for a moment, the hypothesis is made that galaxies of a given type are intrinsically brighter in the southern sector, it follows that the concentration of galaxies and groups in the northern sky is greater still than under the usual assumption of a constant $\overline{M_m}$. This merely strengthens the argument for local superclustering with a center in the direction of the northern hemisphere.

5. Conclusions

The main conclusions seem to be the following:

a) The large anisotropy in the surface (and space) density distribution of the brighter galaxies ($m < 14$ to 15) is reflected in the velocity distribution.

b) The velocity-magnitude relation differs significantly in different directions of the supergalactic equatorial belt; only a small fraction of the differences may be attributed to systematic variations in the mean absolute luminosity of galaxies in different directions.

c) Because of these effects the ratio of the mean velocity of the Virgo "cluster" (or other nearby groups of the northern galactic hemisphere) to some estimated distance is not a reliable estimate of the coefficient of the universal red-shift; the value so derived is too small, perhaps by as much as 30 to 70 per cent. Hence on the current distance scale $H \approx 120$ to 180 km sec Mpc^{-1} rather than $H \approx 75$ to 125 km as derived from the Virgo cluster and nearby groups in the northern hemisphere (Sandage 1961).

d) No such effects are observed in the supergalactic polar caps where relatively few nearby members of the Local Supercluster interfere with the more distant field galaxies; these regions are therefore best suited to establish the general law of red shifts; in these directions objects having a distance modulus $m - M \geq 30$ to 31 seem to be beyond the local condensation.

e) In other directions objects clearly outside the local condensation should be used to calibrate the expansion parameter. In the general direction of the north galactic pole this condition requires objects having a distance modulus $m - M \geq 34$ to 35, such as the Coma cluster, and in the direction of the south galactic pole $m - M \geq 32$ to 33.

Unfortunately this complicates the task of calibrating the expansion law since primary distance indicators such as novae, cepheids, or HII regions fail beyond $m - M \approx 30$ to 31; secondary indicators based on magnitudes, colors, and diameters of the galaxies themselves will be needed. A joint program for the statistical analysis of the new "Reference Catalogue of Bright Galaxies" now in progress at the University of Texas and at the Statistical Laboratory, University of California may provide the necessary calibration of these secondary indicators.

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1. Example of $V_o(L)$ in equatorial belt for E, L galaxies.

2a, b. Mean velocities $\overline{V_o}(L)$ in polar coordinates. Empty sectors near L = 0° and 180° mark the Milky Way crossings.