STUDIES OF THE VIRGO CLUSTER BASED ON
THE VIRGO PHOTOMETRY CATALOGUE

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ABSTRACT
The Virgo Photometry Catalogue (VPC) is the first independently calibrated general catalogue of galaxies to cover the Virgo cluster since the Catalog of Galaxies and Clusters of Galaxies of Zwicky et al. (1961,1963). It contains 1180 galaxies (including background objects) within a 23 square-degree region centred on the cluster’s core. Photographic surface photometry is presented for 1067 galaxies in the $U$ band, for 1020 galaxies in the $B_J$ band and for 1020 galaxies in the $R_C$ band. All total magnitudes and total colours are extrapolated according to a new system; denoted $t$ to distinguish it from the $T$ system already in use. This paper outlines: the scope of the VPC, the new extrapolation system, some recent findings based on the catalogue and further work in progress.

1. THE CATALOGUE
The VPC is based primarily on four U.K.-Schmidt plates (one $U$, two $B_J$ and one $R_C$) which were digitised using the Royal Observatory Edinburgh’s COSMOS two-dimensional scanning microdensitometer. The centre of the VPC field is $R.A. = 12^h 26^m$ and $Dec. = 13^\circ 08'$ The galaxy sample consists of non-stellar objects brighter than $B_J = 19.0$; the completeness limits being $B_J \approx 18.5$ for the northern half of the survey area and $B_J \approx 18.0$ for the southern half. Parameters listed for catalogued galaxies include: equatorial coordinates, morphological types, surface-brightness profile parameters (as well as the original surface-brightness profiles), $U$, $B_J$ & $R_C$ isophotal and $t$-system total magnitudes, transformed $B_t$ magnitudes, $(U - B_J)$ & $(B_J - R_C)$ equal-area and $t$-system total colours, apparent angular radii, ellipticities, position angles, heliocentric radial velocities, alternative designations and cluster-membership assignments. All magnitudes and colours were derived from numerical integrations of segmented plate-scan data, except for (in 109 cases) saturated or (in 51 cases) inextricably merged images; the segmentation software having been able to cope with the vast majority of image mergers.

The $U$-band photometry was calibrated by means of 280 $U$-band aperture-photometry measurements from the literature; whilst the $R_C$-band photometry was calibrated by means of 16 published $R_C$-band aperture-photometry measurements, as well as four $R_C$-band CCD frames. The $B_J$-band photometry was calibrated by means of 239 pairs of $B$- and $V$-band aperture-photometry measurements from the literature and the transformation: $B_J = B - \alpha (B - V)$, with $\alpha = 0.35$. However, were the [now more fashionable] value of $\alpha = 0.28$ to be more accurate, the VPC’s $B_J$ photometric zero point may be too faint by of the order of 0.07 mag.

The author would therefore not wish to pretend that the zero-points of the VPC’s $B_J$ and transformed $B$ magnitude scales are of the highest accuracy attainable. However, from the comparisons between the VPC’s surface photometry and well-documented photoelectric aperture and CCD surface photometry in the literature, as described by Young (1994) and Young & Currie (submitted), it appears very unlikely that the VPC’s $B_J$ and/or transformed $B$ zero points could be too faint by more than 0.1 mag., whilst it is even more unlikely that they could be even marginally too bright.

An early version of the catalogue has already been presented by Young (1994) but the final version is presented by Young & Currie (submitted), in which the minor differences between the two versions of the catalogue are quantified. The main difference between the two versions is that in the final version, the $B_{Jt}$ values are derived directly from Equation 3 rather than by a slightly less rigorous numerical method. The final $B_{Jt}$ values are on average marginally brighter by 0.004 mag. Work already based on the early version of the catalogue includes: Young & Currie (1995) (whose subsample of 64 VPC dwarf ellipticals are on average 0.026 mag. brighter in the final catalogue) and Drinkwater et al. (1996).
2. THE $t$ SYSTEM FOR ESTIMATING TOTAL MAGNITUDES

This new system differs fundamentally from the $T$ system of de Vaucouleurs et al.’s (1976, 1991) Second and Third Reference Catalog of Bright Galaxies (RC2, RC3) and of de Vaucouleurs & Pence (1979); in that (1) extrapolations of photometric profiles do not rely on any prior morphological classification and (2) the smearing effects that degrade the resolutions of photometric profiles are not neglected. In this system, two-dimensional digital galaxy images are [unless already of sufficiently low resolution] first smoothed numerically (ideally convolved with a radially symmetric Gaussian function) in order to reduce their resolution sufficiently that their surface-brightness profiles can be modeled by Sérsic’s (1968) law irrespective of galaxy morphological type:

$$\sigma(r) = \sigma_0 \exp\left[-\left(\frac{r}{r_0}\right)^n\right],$$

in which $r$ is the reduced radial distance ($\sqrt{\frac{r_{\text{major}}r_{\text{minor}}}{}}$), $\sigma(r)$ is the surface brightness in linear units of luminous flux density at $r$, $\sigma_0$ is the central surface brightness and $r_0$ is the angular scale-length. In standard logarithmic surface-brightness units, the central surface brightness is therefore $\mu_0 = -2.5\log_{10}\sigma_0$ in mag.arcsec$^{-2}$, whence the equivalent expression:

$$\mu(r) = \mu_0 + 1.086\left[-\left(\frac{r}{r_0}\right)^n\right],$$

enabling values of $\mu_0$ and $r_0$ to be obtained by linear regression when the optimum value of $n$ has been derived. The analytical solution:

$$2\pi\int_0^{\infty} \sigma_0 r^2 \exp\left[-\left(\frac{r}{r_0}\right)^n\right] dr = \frac{2}{n} \pi \sigma_0 \Gamma\left(\frac{2}{n}\right) r_0^2,$$

then yields an estimate of the total luminous flux within the pass-band concerned.

Clearly, this generalisation incorporates not only the $r^{\frac{1}{4}}$ law ($n = \frac{1}{4}$) but also exponentials ($n = 1$) and Gaussians ($n = 2$) as well as both intermediate and more extreme cases, though it is still a one-component model. As is evident from Young & Currie (1994, 1995) images of dwarf-elliptical galaxies whose surface-brightness profiles can be fitted well by a single component model do not generally need to be smoothed except when they are nucleated.

This extrapolation system has already been outlined by Young & Currie (1994, 1995). It is described in more detail by Young et al. (submitted).

3. ERRORS IN EXISTING MAGNITUDE SCALES

A magnitude scale was originally established for Virgo galaxies by Zwicky et al. (1961) and Zwicky & Herzog (1963) in Volumes I and II respectively of their Catalog of Galaxies and Clusters of Galaxies (CGCG). de Vaucouleurs & Pence (1979) later applied transformations to the CGCG magnitudes of objects in the direction of the Virgo cluster (as well as to magnitude values quoted in two other less-extensive catalogues for these CGCG galaxies) with a view to reducing them to their blue-band total-magnitude ($B_T$) scale based on their $T$-system extrapolations.

These transformed magnitudes were then used by Binggeli et al. (1984) for the zero-point calibration of Binggeli et al.’s (1985) blue-band Virgo Cluster Catalog (VCC), which went much deeper than either the CGCG or de Vaucouleurs & Pence’s catalogue. As the VCC is the most extensive catalogue of Virgo galaxies published to date, it has become a standard reference work and the main source of magnitudes for Virgo galaxies, even though it lacks any independent zero-point calibration.

For the brighter Virgo galaxies, another frequently used source of magnitude measurements has long been the Reference Catalog of Bright Galaxies series. The latest edition in this series is the RC3. This catalogue is primarily a compilation of magnitudes from different sources transformed to a common system, but its magnitude values for Virgo galaxies were not independently calibrated.

Comparisons between the magnitude scales of the VPC and those of existing studies of Virgo galaxies (as well as between the existing studies themselves), suggest serious systematic errors throughout most of the literature. Young (1994) has already found that the transformations of de Vaucouleurs
& Pence (1979) appear to suffer from very serious systematic errors at the faint end, that lead to over-estimates of galaxy luminosities by $\lesssim 0.7$ mag. for their Table 2 objects and $\lesssim 1.1$ mag. for their Table 4 objects. The transformations used in the compilation of the RC2 and by de Vaucouleurs & Pence were eventually renounced, and thereby superseded, in the RC3 (1991). However, in the meantime, Binggeli et al. (1984) based the VCC’s magnitude scale on the original work of de Vaucouleurs & Pence. Young (1994) found that the VCC appears to overestimate galaxy luminosities by $\lesssim 0.7$ mag. at $B_T = 16.5$ (or their $B_T \approx 15.8$).

The RC3 transformations, whilst a significant improvement on those of de Vaucouleurs & Pence still appear to lead to significant over-estimates of galaxy luminosities faintward of $B_t \sim 15$. The mean systematic error may still be as much as $\sim 0.5$ mag. at $B_t = 16.0$. It can be attributed in large part to the application of inappropriate (e.g. $r^+$-law) extrapolations to low surface-brightness galaxies (such as IC 3475 which Vigroux et al. 1986 have already demonstrated to have an exponential profile) during the compilation of the RC3, as discussed in detail by Young et al. (submitted). Therefore, the RC3 magnitude scale may well suffer from similar systematic errors in other fields with high surface number densities of low-surface-brightness galaxies, such as the direction of the Fornax cluster.

The main conclusion thus far is therefore that differences between the extrapolations of the pre-RC3 $T$ system and those of the $t$ system, are primarily responsible for the extremely large systematic differences between the total magnitudes quoted in both the RC2 and the VCC on the one hand, and those quoted in the VPC on the other hand. Disagreements between the zero-points of the VPC’s surface photometry and those of previously published photoelectric (including CCD) photometry cannot be the cause, because they are generally small. Saturation effects cannot be the cause either because care has been taken to flag all saturated image profiles and in any case the observations were made under poor seeing (370 and 177 FWHM). The example of IC 3475 can be used to illustrate the point. Vigroux et al. (1986) extrapolate its $B$-band profile to $r = \infty$ according to the exponential law and obtain a total magnitude of 14.47. In the RC3 on the other hand, aperture photometry for the same galaxy is extrapolated as if it obeyed the $r^+$ law yielding $B_T = 13.82$. From Young (1994) and Young & Currie (submitted), differences between the $B$- & $V$-band aperture photometry used in the RC3 and simulated-aperture photometry based on unsmoothed VPC $B_J$-band plate-scan data are known to be negligible [by transforming between the $BV$ and $B_J$ systems]. Nevertheless, the VPC’s $B_J$ value of 14.10 corresponds to a transformed $B_t$ magnitude indistinguishable from Vigroux et al.’s value, and is thereby $\approx 0.7$ mag. fainter than the RC3 value.

The preliminary evidence for serious systematic errors in the faint ends of the existing magnitude scales has already been presented by Young (1994), whose work is being supplemented by $B$ and $V$-band wide-field CCD frames obtained earlier this year (1996). These frames cover virtually the whole of the VPC survey area and will yield independently calibrated $t$-system total magnitudes for the 109 brighter Virgo galaxies whose photographic photometry was saturated in the VPC. A more detailed study quantifying the systematic errors as a function of magnitude (i.e. not just at the faint end) will subsequently be presented by Young et al. (in preparation).

4. THE VIRGO CLUSTER’S DISTANCE AND STRUCTURE

Most attempts to measure the Hubble parameter have long been based on distance measurements to Virgo-cluster galaxies. There are probably two main reasons for this. First, it is the nearest cluster in which a full complement of morphological types is represented. It has therefore been possible to apply a wider variety of different distance indicators to Virgo galaxies than it has been for other clusters at similar redshifts such as Fornax or Leo. Second, Virgo has the added advantage of being easily observable from observatories in both the Northern and Southern hemispheres.

Virgo’s popularity as a pivotal step in the cosmic distance scale has nevertheless not been without its difficulties and controversies. Until recently, the possibility that the spatial extent of the Virgo cluster may have considerable line-of-sight depth was not taken seriously. Although Pierce & Tully (1988) suggested the ‘possible presence of superposed foreground and background galaxies’, it was not until the distance-scale work of Tonry et al. (1990) and Tonry (1991) that any author was prepared to stand by the case for considerable depth. However, these authors did not confront the potentially
embarrassing issue of the cluster’s elongation ratio in the line of sight, which would have to exceed 5:1 in order to explain the depth in their derived galaxy distributions. Other authors have quite understandably tended to explain any apparent depth effect in Virgo galaxy distributions in terms of random observational errors and scatter intrinsic to the distance indicators employed.

The first authors not to avoid the elongation issue were Fukugita et al. (1993). These authors suggested that the Virgo cluster’s spiral galaxy distribution is in fact filamentary in shape, rather than approximately spherically symmetric [as had been assumed before], with spirals lying at distances from 13 Mpc all the way to 30 Mpc. Young & Currie (1995) also found a considerable depth effect, that they could not explain away in terms of intrinsic scatter in their L-n and R-n indicators; this time in the distribution of 64 VPC dwarf elliptical galaxies in the direction of the Virgo cluster’s core itself. They also found preliminary evidence for a foreground cluster at a distance of about 9 Mpc, which led them to suggest that the depth effect may be due to the projection of more than one distinct galaxy concentration in the same sight line. This would avoid the need for elongation ratios of the order of 5:1.

Further work is already in progress to enlarge the dwarf-elliptical galaxy sample (by extending the morphological-typing limit of the VPC to fainter magnitudes) so that a representative sample of tracer galaxies can be defined. This should enable the separation of separate galaxy concentrations in the same sight line should they be present. This work will be supplemented by as yet unpublished radial-velocity measurements for Virgo dwarfs, which will enable a kinematical study of the dwarfs.

5. FURTHER STUDIES BASED ON THE VPC

An investigation is already underway into the luminosity functions of Virgo dwarfs. This new work on the subject will have the triple benefits over previous studies of: galaxy samples selected according to objective criteria, independently calibrated machine generated magnitude measurements and the consideration of depth effects. Another study based on the VPC galaxy sample will be a pencil-beam survey in the Virgo direction. This study will be enhanced by new velocity measurements which will supplement those of Drinkwater et al. (1996).

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