RECENTLY DEVELOPED DISTANCE CRITERIA

G. Paturel
Observatoire de Lyon
69230 Saint-Genis-Laval

INTRODUCTION

The problem of the determination of distances in astronomy (the so-called problem of the distance scale) is a very old and important problem. About 280 BC Aristarchus of Samos, the famous greek astronomer of the Alexandrian school, already devised a method to find the relative distances to the Sun and Moon in terms of the size of the Earth. Later, Eratosthenes (about 200 BC), another greek astronomer, measured the Earth's diameter; so the zero-point of this first distance scale was fixed.
Now we are interested by extragalactic distances but the same approach is made : (i) determination of relative distances (ii) determination of the zero-point to obtain absolute distances.
Some distance criteria can be used to determine the zero-point. These criteria cannot generally be used at a great distance. They permit a comparison between galactic objects, like Cepheids, Novae, Supergiants ..., globular clusters..., and the same counterparts recognized in external galaxies. Often application is limited to nearby galaxies. In a first section we will briefly present this kind of distance criteria. For more distant galaxies other criteria must be employed, the zero-point being here fixed with nearby galaxies whose distances are known from the preceding step. We will discuss these criteria in a second section.

1-DISTANCE CRITERIA BASED ON COMPARISON WITH GALACTIC OBJECTS.

Each galactic object could be used as distance indicator as far as it can be recognized in external galaxies. We cannot mention all papers concerning studies on galactic objects, but two still recent series of papers have been memorable in this way. The first series (Sandage and Tammann, 1974-1982) was based on the calibration of galaxies whose distances are known from Cepheids (Sandage and Tammann, 1968). In the second series of papers Vaucouleurs (1978-1979) used various primary calibrators (Novae, Cepheids, RR lyrae, AB Supergiants, eclipsing variables) claiming "tradition notwithstanding, distances derived from

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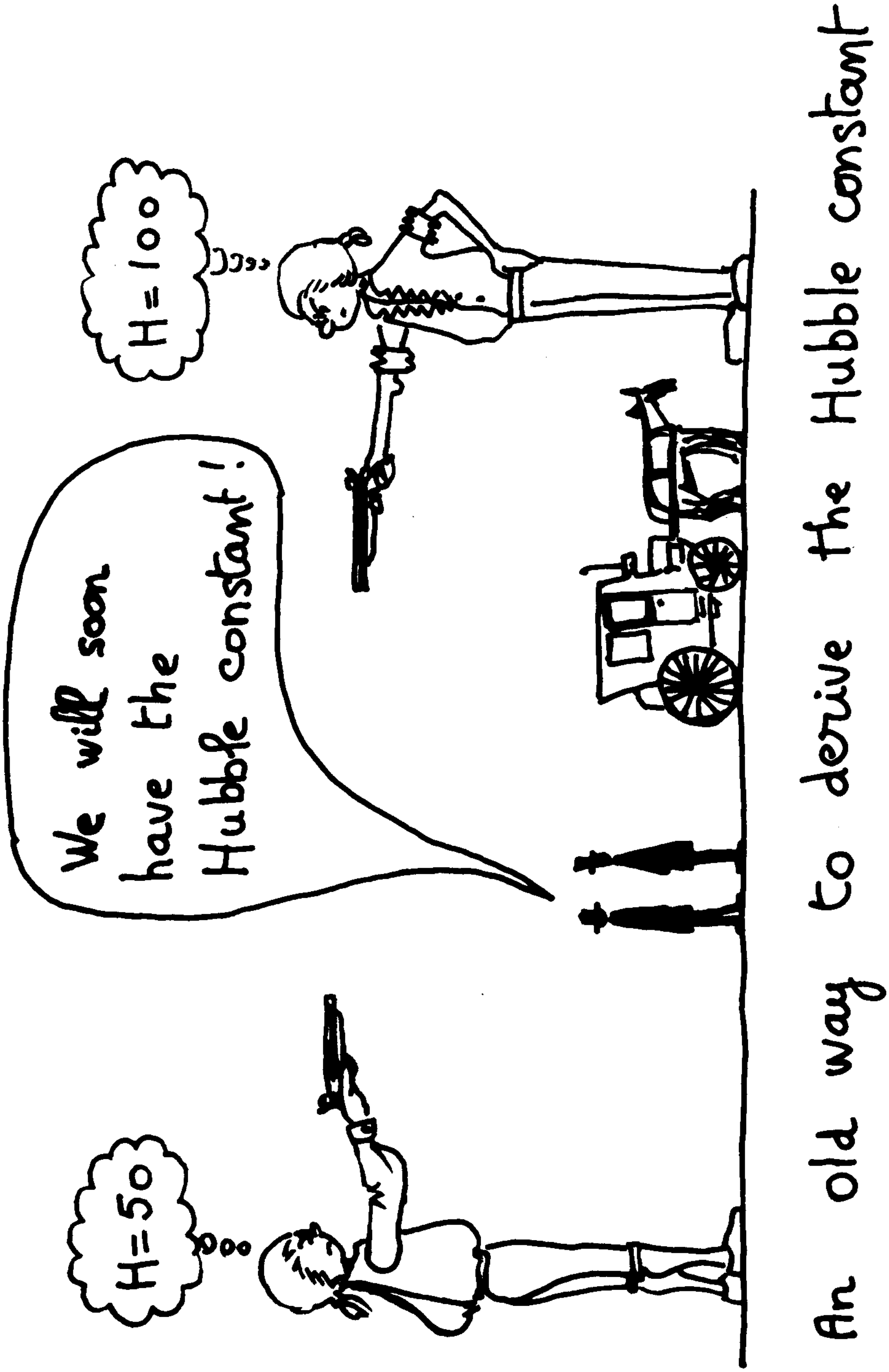

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Cepheids calibrated in open clusters deserve not greater weight than the others".

It is not our intention to give full details on each primary distance indicators; such a review already exists (Sersic, 1980). We will just give a list of these potential indicators and for each of them we will try to see how it can be directly calibrated and what is its reach.

1-1- Cepheids

In the last paper of the first series (Sandage and Tammann, 1982) two new galaxies calibrated with Cepheids are added : Sextans A (Sandage and Carlson, 1982) and Ho IX (Sandage, 1982). Moreover Sandage and Carlson announce thatCepheids have been found in six other galaxies. The absolute magnitude of galactic Cepheids is tied to distance of Hyades cluster. Vaucouleurs from a mean of different sources adopts the distance modulus μ (Hyades) = 3.29, while Sandage and Tammann adopt μ (Hyades) = 3.03 arguing that RR Lyrae stars in LMC and SMC do not support a larger distance modulus. The absolute mean magnitude of Cepeheids is about $\langle M \rangle$ =-3.60. Assuming it is possible to measure 21th apparent magnitude in an external galaxy, the reach of Cepheids criterion could be a distance modulus of μ= 24 or 25.

1-2 Novae

Novae at maximum have an absolute magnitude M which depends on the decay rate parameter (Vaucouleurs uses also the magnitude 15 days past maximum). The calibration used by Vaucouleurs (1978a) is based on galactic Novae with distances derived from expansion parallaxes or interstellar line intensities. The reach of this criterion could be μ = 28.

1-3 RR Lyrae

The absolute luminosity of RR Lyrae stars can be considered as constant although various effects are probably mixed (period, metallicity, spectral type effect) according to Kukarkin (1974). The mean absolute magnitude calibrated from statistical parallaxes (Vaucouleurs, 1978a) is about $\langle M \rangle$ = 0.8. This calibration can also be obtained from a color-magnitude diagram of the parent globular cluster, but the fit on the ZAMS depends thus on the Hyades distance modulus.

1-4 Supergiants

Vaucouleurs uses the accurate classification of stars due to Barbier, Chalonge and Divan (Chalonge and Divan, 1953, 1973) and deduces the distance of Magellanic Clouds expressed in terms of the distance of the h and χ Perseus galactic cluster. But the distance of this cluster is still based on the Hyades modulus.

Sandage and Tammann use the brightest (or the mean of the three brightest)) blue or red supergiants (Sandage and Tammann, 1974a, 1974b, 1982). In principle the absolute magnitude of these stars could be deduced from a comparison with the same stars in our Galaxy (Humphreys, 1978) but

Sandage and Tammann calibrate also with external galaxies with distances known from Cepheids. In their paper VIII Sandage and Tammann do not use the blue supergiants because of the correlation between the absolute magnitude of these stars and the absolute magnitude of the parent galaxy.
Irregular blue variables (Hubble-Sandage stars) are unsuitable as distance indicators according to Sandage and Tammann (1974b).
In conclusion Supergiants stars being very luminous have a long reach and can be measured as far as 10 Mpc ($\mu = 30$).

1-5 Supernovae

This kind of extremely luminous sources has a high potentiality ($\mu = 39$) which can lead to a very direct application (Sandage and Tammann, 1982). In principle it is possible to compare Supernovae with counterparts in our galaxy to provide a calibration but the distances of galactic Super novae are still poorly determined so that this way is not yet useful (Branch, 1982). It is to be noted that some problems are still remaining for the use of Supernovae as distance indicators : Does the absolute magnitude at maximum depends on the decay rate factor (Branch, 1981) ? What is the dependance of this absolute magnitude on the morphological type if the parent galaxy ?

1-6 HII regions and Super-associations

The brightest or ringlike HII regions can be used as distance indicators. The measurement of isophotal diameters is required (Kennicutt, 1979a,b) although the ringlike HII region diameters are probably less sensitive to the limiting surface brightness. A recent catalog (Hodge, 1982) identifies 16293 HII regions in 223 galaxies and permits a study of radial distribution of HII regions.The comparison with galactic HII regions is not easy because of the wide range of linear diameters; generally this criterion has been used as a secondary criterion (i.e. calibrated with nearby galaxies). Moreover another problem is set by the correlation of HII region diameters with the absolute magnitude of the parent galaxy (Sandage and Tammann, 1974a).
Super-associations of OB stars and HII regions easily identifiable on color photographs (Wray and Vaucouleurs, 1980) could be useful up to 100 Mpc while normal HII regions lead to a distance criterion having a reach of 10 or 20 Mpc.

1-7 Globular clusters

Globular clusters can be identified in external galaxies at the distance of the Virgo cluster (Hanes, 1977, 1979) and are good candles because they are out of the obscured region and because the distance of galactic globular clusters can be determined from RR Lyrae stars or from a fit on the ZAMS (i.e using the Hyades modulus). The luminosity function of globular clusters seems universal but the diameter of the brightest globular cluster is related to the absolute magnitude of the parent galaxy.

Some other potential distance indicators have been proposed : eclipsing binaries (Vaucouleurs, 1978a); W Virginis stars (Van den Bergh, 1977). They have not yet received a large application.
In conclusion of this section it is clear that the primary calibration requires an improvement of the galactic distances because now any extragalactic scale is principaly based on the Hyades distance modulus for which an uncertainty of about 5 or 10 percent subsists. The european satellite HIPPARCOS will be probably of the first importance to fixe the zero-point of future extragalactic distances by giving very high accuracy stellar parallaxes. The Space Telescope will be also very important to detect for example Cepheids in Virgo cluster galaxies and to give a large and accurate sample of primary calibrators.

2-DISTANCE CRITERIA BASED ON COMPARISON WITH NEARBY CALIBRATING GALAXIES

At this stage we will consider a galaxy as a whole. Thus the corresponding distance criteria would be useful, in principle , so far as a galaxy can be recognized. We will now consider each of these criteria.

2-1 Diameter-luminosity relation (also called surface brightness method)

This criterion leads to a relative distance from apparent magnitude and apparent diameter (Holmberg, 1964; Heidmann, 1967; Paturel, 1979) but it is not very accurate with the current systems of apparent magnitude or diameter (e.g. B_T^o and log D_o). In other words, the mean surface brightness for these systems depends only a little on the luminosity (Kennicutt, 1982). We will see in the last section how the use of IR-magnitudes makes this criterion more useful.

2-2 Luminosity classification

Van den Bergh (1960 a,b,c) has shown that the morphology and the absolute magnitude of a spiral galaxy are correlated. In a recent paper he makes a comparison between luminosity classes recently produced by Sandage and Tammann (1981) and his own estimation. The fair agreement shows that classification is "not just an art but also a science !". The standard deviation of the difference between these systems is 0.68 luminosity class. After Van den Bergh, Sandage and Tammann (1974d) give an absolute calibration of the luminosity classes but a bias found by Bottinelli and Gouguenheim (1976) leads to look for a new calibration. Sersic (1980) gives a calibration adapted from Bottinelli and Gouguenheim (1976), Mould et al. (1980) and Van den Bergh (1980). Vaucouleurs (1979a) combines the luminosity class L with the morphological type code T (Vaucouleurs et al., 1976) into a luminosity index Λ = (T+L)/10 which is more closely correlated with absolute magnitude. Note that an inclination effect must be considered either in absolute calibration (Sandage and Tammann, 1974d) or in definition of L (Vaucouleurs, 1979a). Kennicutt (1982) looks for correlation between quantitative spiral properties and absolute magnitude in order to understand origin of luminosity classes. He finds a dependance of luminosity on arm widths normalized to the diameter spiral pattern.

2-3 Inner Ring structures

The morphological classification given in the second Reference Catalog (Vaucouleurs et al., 1976) differentiates families of galaxies (barred B, intermediate AB, normal A). This family, coded F ($-1<F<1$), is used for ring galaxies, combined with morphological type T and corrected luminosity class L_c to derive the linear diameter of the ring structure (Vaucouleurs and Buta, 1980; Buta and Vaucouleurs, 1982a,b,c). Such a ring structure can be identified at great distances. This method is independent on galactic absorption and on the inclination of the studied galaxy. The absolute calibration cannot be made with nearby galaxies because of the lack of ring galaxies in the Local Group (excepting our Galaxy) Buta and Vaucouleurs compare their measurements to those given by Kormendy (1979) and by Pedreros and Madore (1981). A good agreement is found showing the reliability of such measurements.

2-4 Color magnitude relation

This relation, first studied by Baum (1959) from B and V measurements has largely been applied to E and SO galaxies in UBV or ubVr systems. The first question concerns the universality of this CM relation. Several authors find the same relation for different groups (Visvanathan and Sandage, 1977) or clusters (Griersmith, 1982) or field galaxies (Sandage and Visvanathan, 1978). On the other hand, according to Michard (1979a) it is necessary to consider several "sequences" of galaxies depending on their average surface brightness calculated from effective diameters. Michard shows (1979 a,b) that "average surface brightness and U-B color used together provide better estimates of relative luminosities than each of these parameters taken separately". Two results are then tied to this universality : Aaronson et al. (1981) do not find in the infrared the same zero-point for the Virgo and Coma clusters. Michard (1982) find that barred lenticulars are significantly redder than other early type galaxies. He shows also that a possible curvature appears on the CM diagram. Thus, we can ask : How many parameters are to be used to reduce the "cosmic scatter" ?

Note that the CM relation for E and SO galaxies is generally used as a relative distance criterion calibrated for example by assuming a given Hubble constant or a given distance for the Virgo cluster.

UBV photometry is not useful to derive a relation for spiral galaxies but extension in the infrared by Visvanathan (1981) and independently by Tully and al. (1982) and Wyse (1982) permits for the first time to use CM relation for spiral galaxies. The color m(visible) - m(IR) seems sensitive to the ratio old giants/young blue stars and such a CM relation could indicate that the star formation rate is directly tied to the galactic mass. A clear separation appears for gas-rich (spiral) and gas-poor (lenticular) galaxies. The absence of intermediate cases suggests according to Tully et al. that an evolution (as the one found by stoping the star formation in a model of disc)from one branch to the other would be rapid.

According to Tully and al., when the difference between the effective wavelenght of the two systems of magnitude (visible and IR) is great the

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relation is better defined.

2-5 The Tully-Fisher relation

Since the publication by Tully and Fisher (1977) a lot of papers have been dedicated to the study of this relation between absolute magnitude (or linear diameter) and 21-cm line width (Tully and Fisher, 1977b ; Sandage and Tammann, 1976 ; Bottinelli and Gouguenheim, 1977 ; Roberts, 1978 ; Rubin et al., 1978 ; Shostak, 1978 ; Rubin et al., 1980 ; Bottinelli et al., 1980 ; Bottinelli et al., 1982 ; Visvanathan, 1981 ; Vaucouleurs et al., 1982 ; Vaucouleurs, 1982b ; Vaucouleurs et al.,1982b Fisher and Tully, 1981 ; Aaronson et al., 1979, 1980a, 1980b, 1982a, 1982b ; Mould et al., 1980 ; Frogel et al., 1978). Several problems have been set : What galaxies are to be considered : face-on or edge-on galaxies ? What is the optimum level at which to define the 21-cm line width ? How to correct the line width for non-circular velocity ? Is the relation universal (i.e. does the slope depends on the morphological type or of the system of magnitude) ?

The choice of inclination cut-off (Sandage and Tammann, 1976 ; Bottinelli and Gouguenheim, 1977) is important because face-on galaxies give poorly determined 21-cm line width and edge-on galaxies lead to uncertain internal absorption correction. According to Aaronson and Mould (1982a) IR magnitudes avoid this probelm and permit to have good accuracy on both IR magnitudes and 21-cm line widths by using a higher inclination cut-off.

Bottinelli et al. (1980, 1982) have studied the TF relation at three levels (20%, 40%, 50%) and they show that, when proper corrections of non-circular velocity are made, the three levels are equivalent and identical to the maximum velocity rotation as given by interferometric rotation curves. Aaronson and Mould say that this non-circular velocity correction is too high in Bottinelli et al. but can however play some role in explaining the apparent non-linearity in the infrared TF-relation.

The problem of the morphological type dependance (Roberts, 1978) is interpreted as an artefact due either to regression effect (Vaucouleurs et al., 1982) or to extreme morphological types (Aaronson and Mould, 1982a). Finally the TF-relation seems to be useful from early spiral galaxies to late-type dwarf galaxies (Vaucouleurs et al.,1982b).

Another important problem concerns the value of the slope of the TF-relation. Bottinelli et al. (1980, 1982) have shown that the slope of the relation increases when the effective wavelength of the magnitude system increases. This result has been confirmed by Visvanathan (1981) and Aaronson and Mould (1982a) although they do not agree with the slope given by Bottinelli et al. (-5 for blue magnitudes). However the high value given by Rubin et al. (1980) for blue magnitudes seems clearly too high.

The absolute calibration can easily be made by applying the TF-relation to nearby galaxies (e.g. Local Group) whose distances are known from primary indicators. Vaucouleurs (1982b,c) shows that our Galaxy can be used for the calibration of the TF-relation.

Numerous data for blue or IR magnitudes and 21-cm line widths are now available (Vaucouleurs et al., 1976 ; Sandage and Tammann, 1981 ;

Aaronson et al., 1982 ; Fisher and Tully, 1981 ; Bottinelli et al.,1982) so that, despite some difficulties, the TF-relation can be considered as one of the most important criterion for spiral galaxies.

2-6 The Faber-Jackson relation

Faber and Jackson (1976) have demonstrated the existence of a tight correlation between absolute magnitude and velocity dispersion for E and L galaxies. Vaucouleurs and Olson (1982) use this relation as a distance criterion. They show that the slope of the FJ relation increases with effective wavelenght of the magnitude system in a similar manner as the TF relation. Second-order parameters could be necessary (color and/or surface brightness) leading to a generalized FJ relation. The absolute calibration is obtained from distances of spiral galaxies associated with the studied E-L galaxies. Vaucouleurs (1982d) also uses the spheroidal component of our Galaxy as a primary calibrator, because this relation can be applied either to E galaxies or to the spheroidal component of lenticular or spiral galaxies (Whitemore et al. 1979, 1981). Application of this relation would possibly be made in the large range of distance moduli $24 \leqslant \mu \leqslant 35$.

2-7 the simultaneous (or global) method

In order to take into account all the information about a given sample of galaxies we can try to use all the available parameters instead of a limited set of parameters. But, how to do that ?
Any set of parameters $\{P_i\}i=1,N$ can be transformed by linear combination (i.e. without loss of information) in distance independent parameters P_j^o (j=1,N-1), except one P_N. On the other hand it has been demonstrated (Paturel, 1981) that the logarithm of an intrinsic parameter which is not distant invariant (like P_N) can be expressed in first approximation as a linear function of the logarithms of N independent parameters (N is the dimensionality of the problem). Thus we have

$$\log P_N = \sum_{i=1}^{N-1} a_i \log P_i^o + \text{cst.}$$

where each right hand term results directly from observations.

Any choice of a set of parameters P_i(i=1,N) leads, in principle, to a distance criterion as far as the P_i are independent. Unfortunately measurements furnish parameters more or less dependent leading to distance criteria more or less powerful. Each known distance criterion can be recognized in this equation (eye-estimated parameters like T or L must be considered as the logarithm of a parameter P according to the old Fechner's law). Let us give two applications of this relation when a limited set of parameters is used.
We have seen (§2-1) that the mean surface brightness calculated from B_T^o and log D_o is not a good luminosity indicator ; that means that D_o and B_T^o are not independent, they carry nearly the same information. If we

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change one of these systems we can hope to have a new distance criterion. We adopt for example IR magnitudes $H_{-0.5}$ from Tully et al. (1982) instead of B_T^o because they are probably more independent. With the preceding notations we have : N=2 ; log $P_2 \propto$ absolute IR magnitude M_T(IR) ; log $P_1^o \propto$ mean surface brightness m'(IR) calcultated from $H_{-0.5}$ and D_o.
Figure 1 presents the diagram m'(IR) versus M_T(IR) for ten spiral galaxies of the Virgo cluster. A clear correlation is found following what we are expecting.

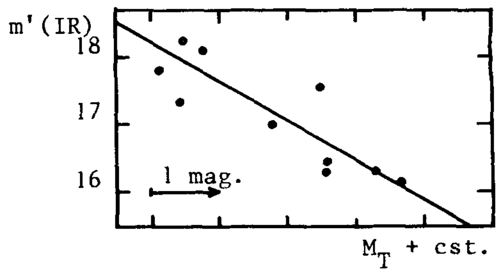

Figure 1. Surface brightness method in the infrared

Another distance criterion has been found on this way. Assuming always N=2 we can use two systems of diameters (These systems must be very different, so we have good hope to build independent parameters). Application of the general relation leads to expect a correlation between log D_H/D_o (where D_H is the apparent HI diameter) and the absolute magnitude .
Figure 2 shows the correlation which was expected (Paturel, 1981). In practice this last distance criterion does not seem very powerfull.

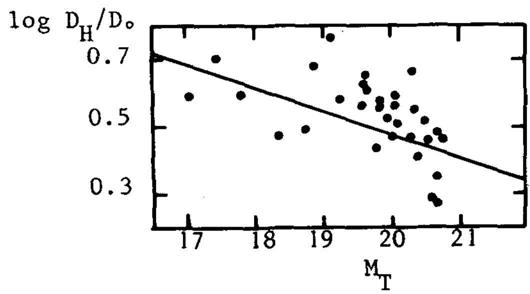

Figure 2. Relation diameter-diameter as luminosity indicator

Finally we see that can build a great number of distance criteria from this manner if we have a great number of parameters. However we do not intend to pursue in this way because we have a more powerful method. If we have a great number M (M>N) of P_i^o parameters we will calculate the principal components U_i using the principal component analysis. These components are independent by construction. We retain then only the significant components (according for example to Guttman's theorem) which contain the same information as all the P_i^o . Finally our preceding relation can be written as :

$$\log P_N = \sum_{i=1}^{N-1} c_i \quad U_i + \text{cst.}$$

but now the U_i components are independent. This last equation can be solved by a least squares method using calibrating galaxies.

Another use of this last equation is to look for galaxies having the same U_i (i=1, N-1) or even the same P_i^o (i=1,M; M>N) as a given calibrating galaxy. In this way we select galaxies very similar ("Sosie" in french) to the calibrating galaxy. From the last equation we deduce that they have the same intrinsic parameter (e.g. the same absolute magnitude or the same linear diameter). Two applications of this method of "Sosies" galaxies have already been made (Paturel, 1981 ; Vaucouleurs, 1982e).

Our general equation can receive a last application. We can apply on a large sample of galaxies the automatic classifcation method (Taxonomy or Cluster analysis) by using the U_i components to judge the membership to a given class. So we define classes of galaxies having at best the same U_i components i.e., according to our relation, the same absolute magnitude . This method permits to define Luminosity classes in a very impersonal manner (Paturel, 1981).

CONCLUSION

Although it seems still possible to improve (i) knowledge of galactic distances (ii) observation in nearby galaxies, in order to have good primary distance criteria it is clear that space astronomy (HIPARCOS satellite and Space Telescope) will probably be a "revolution" in this domain.

Concerning criteria calibrated on galaxies whose distances are known from primary indicators a lot of new data (HI,IR, optical) can already be used with recently developed distance criteria, like the color-magnitude relation for all morphological types of galaxies, the Tully-Fisher relation for gas-rich galaxies, the Faber-Jackson relation... On the other hand the development of modern data analysis (Principal component analysis, Cluster analysis...) would permit a better use of these data. In my opinion it is urgent to centralize all the extragalactic data getting them easily available for each study.

In any case it is probably important to use these criteria always looking for a better understanding of the physics in studied objects. In fine, is it not the chief purpose of astrophysics ?

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