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Autor: Cramer, Noël

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Aspects of Geneva Photometry[1]

Part 5 – Questions of magnitude

NOËL CRAMER

In this fifth part of the article, we look at the multicolour photometric calibration of stellar intrinsic luminosity habitually given as the absolute magnitude M_V. The estimate of the latter quantity is in the majority of cases the only way to assess the space distribution of young stellar populations and, as a consequence, that of interstellar dust. Stars, however, tend to form binary or multiple systems and are subject to a number of physical peculiarities. Such characteristics introduce a significant and unavoidable amount of dispersion regarding the M_V estimate.

5.2.2.2. The absolute magnitude problem. The use of intrinsic colours

We have seen in Part 4 that trigonometric parallaxes measured for nearby stars initially served to establish the first step of the cosmic distance scale. Open clusters then allowed its further extension by associating high mass (i.e. high luminosity) stars, not present in the immediate solar neighbourhood, with the cluster distances and accordingly enabling a determination of their absolute magnitudes.

However, the situation was not satisfactory. Only the absolute magnitudes of the least luminous stars were well determined. Very few stars of mass greater than solar had well established intrinsic luminosities (see Fig 48, part 4). The absolute magnitudes of the latter depended on extrapolations. On a larger scale, however, it is those most luminous stars that act as the basic distance indicators. An M-type dwarf such as Proxima Centauri would have a very well defined absolute magnitude but, at only 100 pc, we would need a very large telescope to be able to obtain accurate photometry of that star which would be of apparent magnitude $m_V = 20$ (see Fig 55). Even our sun which shines so brightly in our sky (Fig 54) would be a 10th magnitude star at that modest distance of 326 light years.

Fig. 54. The Sun, our closest stellar neighbour, observed from the Jungfraujoch Scientific Station. Although its visual absolute magnitude of $M_V = 4.83$ makes it a star of modest luminosity, its proximity at only 1.58 10^{-5} light years gives it an apparent magnitude $m_V = -26.72$ which renders it visible in full daylight!

Hipparcos

It was understood in the 1960s that positional measurements with accuracy greater than 0.01 second of arc were virtually impossible to achieve from ground-based observations; mainly because of variable atmospheric refraction as well as gravitational and thermal influences on the instrumentation. To progress further, it became necessary to do such observations from space. The first suggestions to that effect were made by P. LACROUTE in 1966, but the concept was abandoned in 1970 as it was judged to be technically unfeasible at the time. The idea survived, however, and the HIPPARCOS satellite mission was accepted in 1980 within ESA's scientific programme. The mission name honours the Greek astronomer HIPPARCHUS who established one of the earliest known stellar catalogues in the first century BC. It is also the acronym of *«High Precision Parallax Collecting Satellite»*. The mean errors of the satellite's parallax and annual proper motion measurements were to be of about 0.001 arcsec (1 milliarcsecond, or «mas»). But measuring at that level of accuracy raises a number of difficulties – not only technical – involving, for example, relativistic effects such as the «stellar aberration» due to the satellite's orbital motion around the Earth, or the gravitational lensing along each line of sight due to the mass of the Sun.

The satellite was launched on August 8, 1989 into what should have been a geostationary orbit. Unfortunately, the latter was not achieved due to the malfunction of a «five penny worth» safety device designed to lock the ignition of the apogee motor until it was required, and the satellite was left in its highly elliptic transfer orbit. This had two important consequences: the data flow from the satellite could not be constant and was significantly reduced; the passage through the VAN ALLEN radiation belts during each orbit continually degraded the electronics and the optical characteristics of the instrumentation. The mission was nevertheless saved at the cost of much effort and pursued within specifications with observations ceasing in March 1993. The catalogue containing the astrometric and photometric data for some 120000 stars was finally made public in June 1997.

Apart from the valuable increase of stellar proper motion data, the HIPPARCOS satellite also extended the measurement of trigonometric parallaxes out to the regions where a significant number of the more luminous, but less frequent A- and B-type stars are encountered (Fig 57).

The accuracy of the positional measurement is, nevertheless, still not as good as would be expected for the

[1] Adapted from *Archs Sci. Genève, Vol. 56, Fasc. 1, pp. 11-38, Juillet 2003*. Based on data acquired at the La Silla (ESO, Chile), Jungfraujoch and Gornergrat (HFSJG International Foundation, Switzerland), and Haute-Provence (OHP, France) observatories.

detailed analysis of those more distant stellar populations. But the situation will decisively improve if the proposed European GAIA mission is implemented by ESA. The positional accuracy will then be some 1000 times better than HIPPARCOS thus opening up the field of microarcsecond astrometry extending to almost one third of the Galaxy. The coverage of the sky will also be systematically expanded to the 20th magnitude with 25000 stars per square degree instead of just 3 as is the case for HIPPARCOS.

5.2.2.3 Calibrating M_v

Given a sufficiently large sample of good distance measurements, and a reliable procedure for de-reddening the relevant photometric data to derive the corresponding absolute magnitudes, it would then appear to be a relatively straightforward process to establish a

Fig. 55. The Alpha Centauri system (below) and Beta Centauri (above), a familiar but instructive image serving to illustrate the range of stellar luminosities and the complexity of reality. The triple system formed by Alpha Cen A & B and Proxima Cen (enlarged in inset) are at distances of 1.348 and 1.295 pc (4.39 and 4.22 ly) respectively. Their visual magnitudes m_v are -0.003, 1.332 and 11.084. That means that their absolute magnitudes are 4.36, 5.68 and 15.52. So, Alpha Cen A is 29100 times brighter than Proxima Cen. The almost equally bright ($m_v = 0.596$) Beta Cen lies much further away. Its HIPPARCOS parallax of 6.21 10^{-3} arc seconds places it at 525 ly from us, though with a standard deviation of 9% on the parallax measurement. If we take into account the [B-V] colour excess of 0.057 that de-reddens its apparent visual magnitude to $m_{v0} = 0.439$ (see part 4), we get an absolute magnitude of -5.596. Beta Cen is therefore 9600 times more luminous than Alpha Cen, i.e. 2.8 10^8 times more luminous than Proxima. We thus see that the range of luminosities among «normal» stars is of the order of one billion to one. Actually, Beta Cen is also a triple system. It consists of two B1 giants, each of about 15 solar masses orbiting at a distance of 3 AU and joined by a less luminous B dwarf of some 5M⊙ at about 210 AU. So, its absolute magnitude is actually that of the whole system. This straightforward example shows us that the interpretation of photometry is not «simple» and systematically requires a critical outlook.

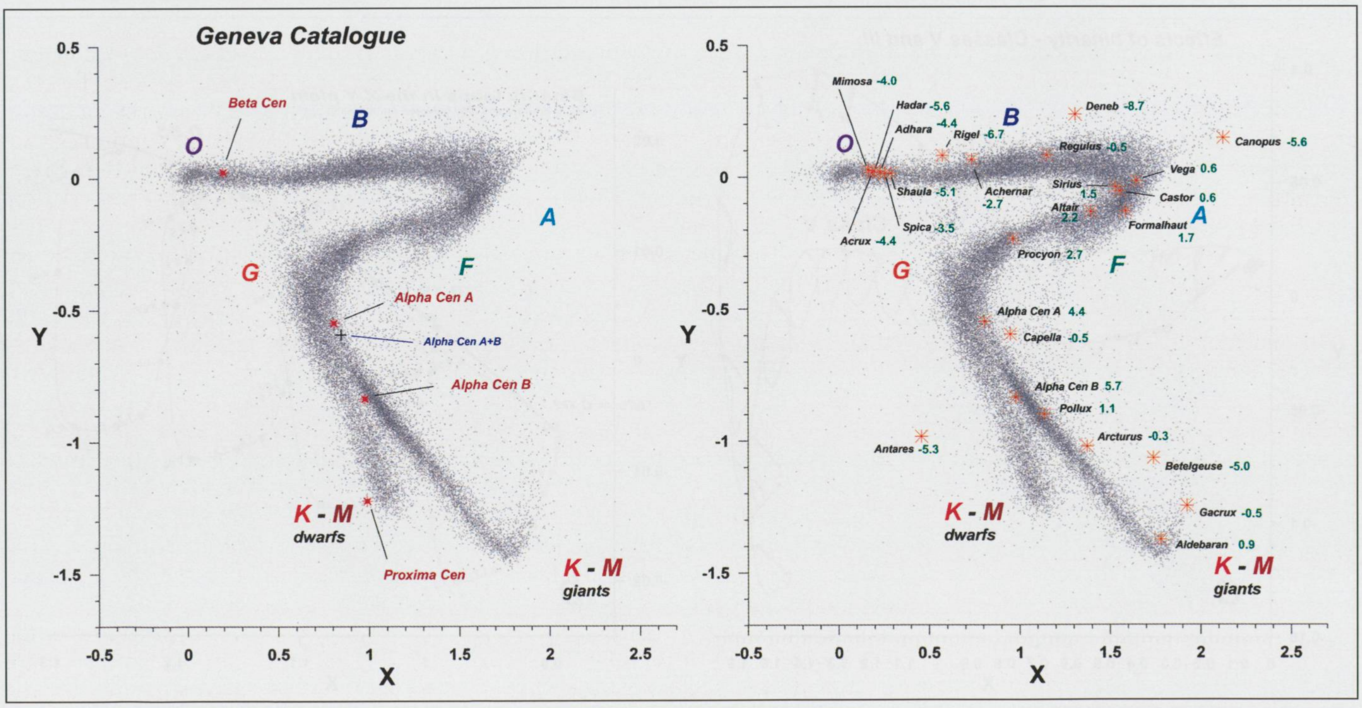


Fig. 56. The colorimetric effects of the great disparity of luminosities of the stars considered in Fig 55 are shown in the X, Y diagram of Figure 56a, left. We have also chosen to show the positions of the 25 brightest stars of our night sky in the same X, Y diagram of Figure 56b, left. The distribution of absolute magnitudes (in green) shows the important role of mass, but also of evolutionary stage (dwarf or giant) as well as the effects of multiplicity. Those with well known distance, and for which the absolute magnitude is calculated on the basis of the apparent magnitude, are too bright for their colours if they happen to be multiple systems (Hadar (Beta Cen), Capella, etc.). Undetected multiplicity is a major source of uncertainty in photometric absolute magnitude calibrations based on colours.

photometric calibration. That is true in principle – but up to a point. Reality is not that simple.

Inevitable noise

Maybe the most ubiquitous source of uncertainty in photometrically derived quantities is undetected stellar multiplicity. Various estimates of the frequency of binaries among B stars encountered in the literature lie within the range of 40% to 60%, i.e. one half to 80% the whole population of *individual* stars of that type are presumably members of a system (see Fig 55). If in a binary system a secondary is detected and the relative contributions of the components can be estimated, standard calibrations can be applied after the corresponding corrections have been made to the observed colours. Otherwise, and actually in the majority of cases, the results derived by photometric calibrations will be affected by unseen companion stars. Indeed, the establishment of a calibration itself may be governed by two different points of view.

The first is to assume that it is impossible to put together a perfectly «clean» sample of single reference stars large enough to carry out a «pure» calibration. In any case, when applied blindly and on a large scale to the real population of stars, such a calibration would systematically be biased since we would not know in advance which of these would actually be a binary or multiple system. So, for statistical investigations, a calibration based on a non-selective sample of data is undoubtedly most suitable.

Fig. 57. The HIPPARCOS satellite measured a consistent sample of stellar categories as shown by the intersection of the HIPPARCOS data with the Geneva catalogue (yellow = also in HIPPARCOS catalogue. Blue = no HIPPARCOS data), to the left. The situation changes, however, if we select according to the quality of the parallax measurement: 20% error at centre and 10% error to the right. This is due to the greater distances of the relatively less abundant massive and luminous stars which lie beyond the range of the satellite. If our object is to establish an absolute magnitude calibration for B-type stars – as is our case – we must accept to use data which can have standard deviations reaching 20% or more so as to have a large enough calibration sample.

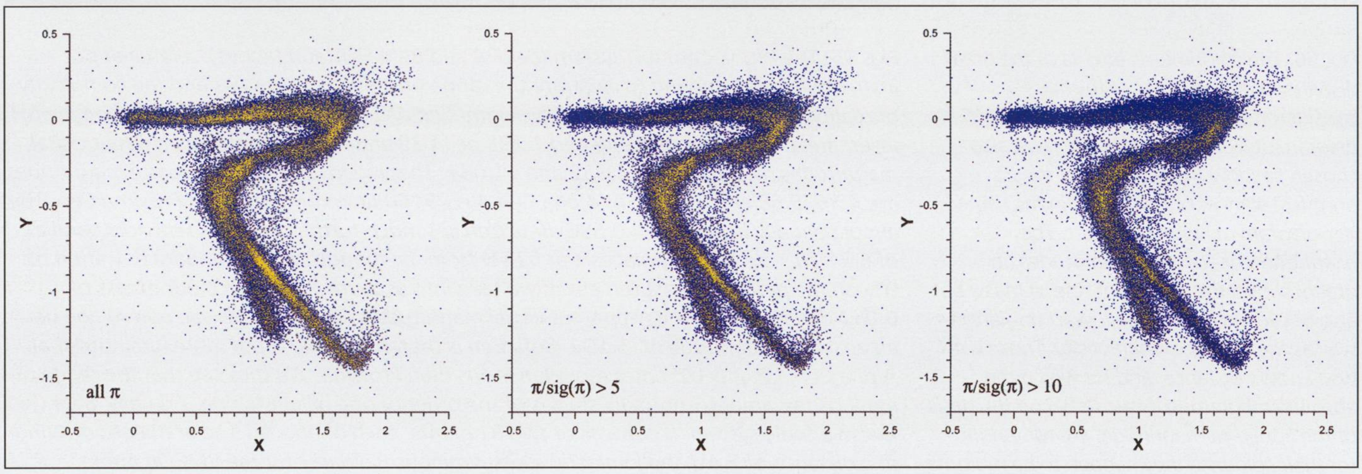
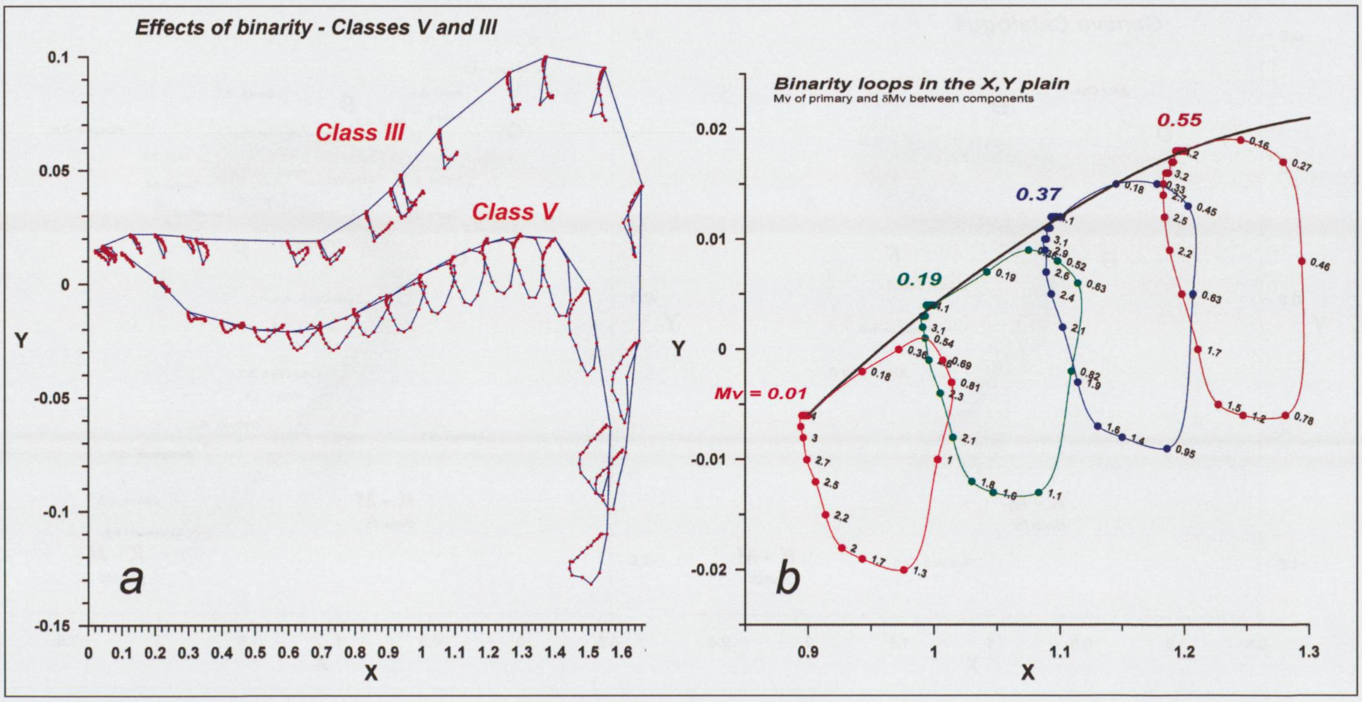


Fig. 58. Binarity loops in the X,Y plane. These are constructed by associating the fluxes of a series of less luminous companions to a set of stars of classes V and III distributed in the plane. Fig 58b is an enlarged portion of 58a, where the magnitude differences of the companion stars are given relatively to the primary. If the companion is identical to the primary, there will be no colour variation but the composite will have an absolute magnitude 0.753 smaller ($-2.5 \log_{10} 2$).



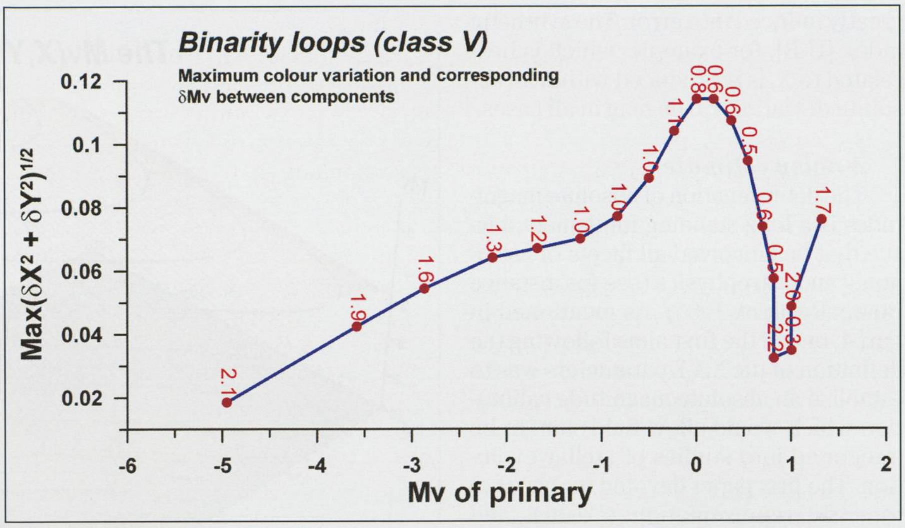


Fig. 59. Effect on colours due to the presence of a companion star. The maximum colour deviation, expressed as a distance in the X, Y plane, is shown as a function of the brightness of the primary (class V). The difference in magnitudes δM_V between components at maximum colour deviation is given for each point. This illustrates the complex behaviour of «noise» created by undetected binaries in a colour-based photometric calibration.

The second approach is to strive, nevertheless, to establish a calibration that is as pure as possible. The major difficulty lies in the choice of the data, some of which will also have to be corrected for multiplicity. Empirical calibrations voluntarily biased in favour of single stars will have to be used carefully in statistical studies. They are, however, best suited for comparisons with synthetic predictions or for the interpretation of theoretical models which most often concern single stars.

In practice, things are not so simple and neither of these two objectives is fully attained. For the advocates of the first, the temptation to repress obviously peculiar data during the calibration process is difficult to resist. For the second, the sheer volume of potentially valuable data that have to be discarded causes a painful dilemma. So, *whatever* may be the character of a given calibration, multiplicity is a major source of noise, and the accurate assessment of its incidences difficult to evaluate.

Here, we illustrate the effects of binarity by their incidence in the X,Y parameter diagram. They are shown with the help of the «binarity loops» of Fig 58a distributed along the standard sequences of class V and III stars. The basis of the class V sequence is a set of 34 points of an empirical zero age main sequence (ZAMS) made with the help of cluster sequences and harmonised over the six normalised indices with the aid of the colour excess ratios of Table 3 in Part 4 (BURKI, CRAMER, MERMILLIOD; unpublished). Each loop is computed at each step of the ZAMS by adding the fainter portion of the same sequence to the primary, one-by-one. The same operation is carried out along the class III sequence, but with primaries having M_V estimated by a calibration of the X,Y plane and with intrinsic normalised indices computed by the relations given in Part 4. The less luminous ZAMS stars are then added as before. The figure shows that the behaviour is quite complex and that the effects are not negligible even in this case of «simple» binarity. The shapes of the loops in photometric diagrams always reflect the general shape of the less luminous part of the sequence. The more contorted is the lower part of the sequence, the more so are the loops.

A portion of the figure is enlarged in Fig 58b, so as to better show the effect of the magnitude difference δM_V between the two components. We see that the maximum deviation occurs at different δM_V for different M_V of the primary. This is best illustrated in fig 59 where the maximum colour deviation expressed as «Euclidian distance» (square root of the sum of the squares of the deviations) is plotted as a function of the M_V of the primary (the two cases at $M_V = 0.82$ and 1.00 are bimodal).

Determinations of photometric sensitivity of this kind can be of some use within the context of colour-dependant bias estimation in the selection of «pure» calibration samples. Spectroscopic detection of binaries becomes more difficult when δM_V exceeds one magnitude, just where photometry is locally most sensitive regarding binarity for the most luminous stars – i.e. the greater is the δM at maximum photometric distance – the more vulnerable the calibration data become to multiplicity that is undetected by other methods.

Regarding the incidence of binarity on the determination of colour excesses, it is clear that in a two-colour representation, such as the U,B,V diagram, nothing can be done for unknown binaries. The effect will quite generally be to overestimate the excess (up to a few 10^{-2} mag) as the presumed zero-point will be taken by default at the standard sequence which is bluer. The consequence is to overestimate total absorption A_V by up to almost 0.1 mag for late B binaries. But, since binarity affects the X,Y parameters in the sense of the composite, one expects the intrinsic colours that are estimated by these parameters to follow – up to a point – the effects operating on the true indices. This is indeed partially realised as shown in CRAMER (1999) and colour excesses derived by that method are therefore closer to their true values.

Rotation, which is an important feature particularly among early-type stars, is also a significant cause of dispersion in photometric diagrams. Rapid rotation tends to deform a star, reducing its polar diameter and increasing its equatorial size. Recent observations done with the ESO VLT telescope have shown, for example, that the fast rotating star Achernar has an equatorial radius 60% greater than its polar one. Surface gravity and temperature decrease at the equator and increase at the poles. A star's colours are modified and depend on its inclination relative to the line of sight. The relative effects of rotation are difficult to assess observationally with current techniques, and are best estimated with the help of theoretical atmosphere models. An early study giving Geneva synthetic colours of these effects was made by MAEDER and PEYTREMANN (1970) for a variety of masses, rotation velocities and apparent inclinations. One model ($5M_\odot$) lies within the validity region of our calibrations and has been used in earlier publications (CRAMER and MAEDER 1979; CRAMER 1984, 1994). The general effect, all inclinations considered, is to displace the colours in the sense of decreasing gravity and temperature with increasing rotation velocity. The greatest displacement is in the X parameter with a maximum deviation $\delta X = 0.231$ mag. The intrinsic colour estimators are, however, not greatly induced into error. The synthetic index [U-B], for example, which is best related to X, is reproduced within an absolute deviation < 0.06 mag in all cases.

A noisy estimate

The determination of absolute magnitudes is a long standing fundamental issue that has involved all facets of astronomy and astrophysics (see for instance ROWAN-ROBINSON 1985). As mentioned in Part 4, one of the first aims following the definition of the X,Y,Z parameters was to establish an absolute magnitude calibration which would allow field stars to be integrated into studies of stellar evolution. The first paper devoted to that photometric representation (CRAMER and MAEDER 1979) thus also discussed an absolute magnitude calibration based on the X,Y parameters. Virtually no primary measurements of distance were available for B stars at that time, and the calibration relied essentially on cluster distance modulus determinations published in the literature. The calibration consisted of a succession of segments along X for which specific quadratic relations were fitted locally. The reference data were voluntarily biased against binarity, when possible, and included a few bright giants and supergiants. The global standard deviation over the residuals amounted to 0.38 mag for the calibration sample of 199 stars.

Subsequently, several (unpublished) calibrations were made with the object of improving the estimate and expanding the range of validity. The last of those was published in the appendix of RABOUD et al. (1997) and was based on the study of 30 solar composition clusters done by MEYNET et al. (1993). A third degree polynomial form in X and Y similar to those of the intrinsic colour estimators discussed above was used. There too, the biasing toward single stars was carried out by an iterative process. The brightness of binaries is systematically underestimated in an absolute magnitude versus colour relation, shifting those belonging to clusters apparently into the foreground. Such stars were removed from the basic sample until the distributions around the mean estimated distances became symmetrical. For that calibration also, the standard deviation over the residuals was found to be 0.40 mag over the remaining 483 reference stars.

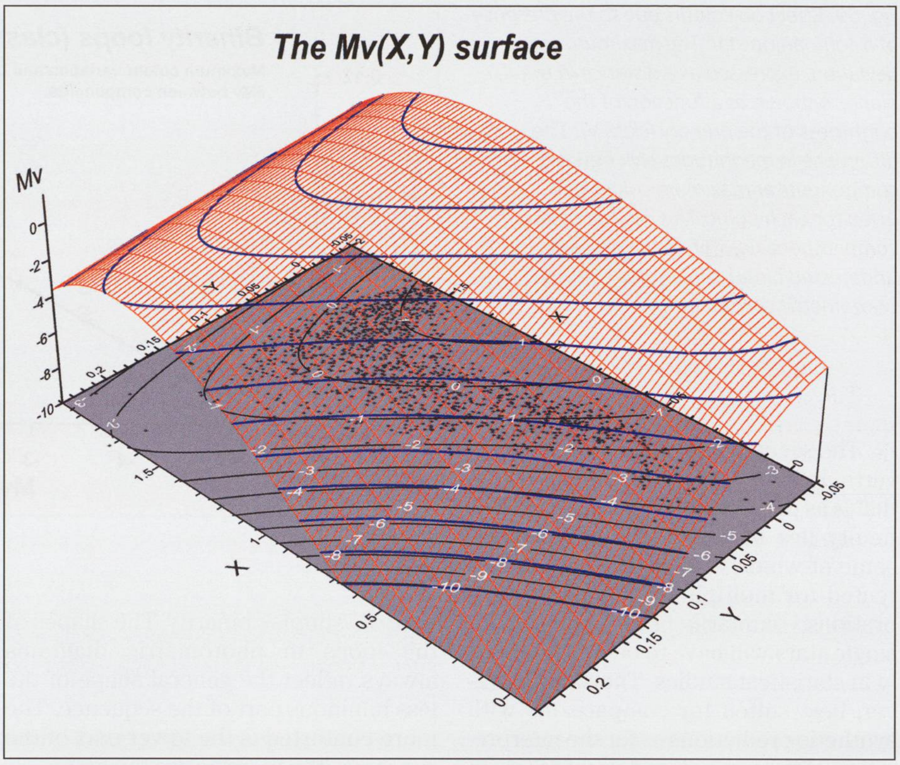
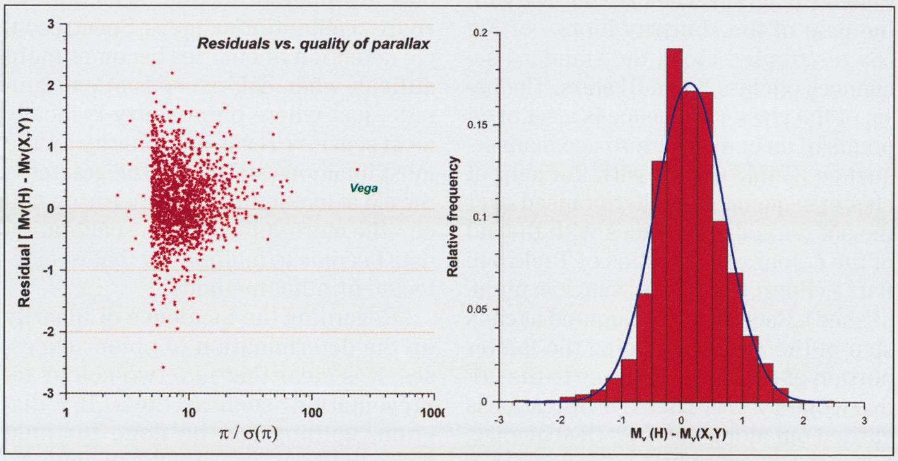


Fig. 60. 3-dimensional representation of the absolute magnitude calibration obtained with the HIPPARCOS satellite parallax data. The calibration data points are projected on the horizontal plain with the relation's contours.

As mentioned above, the most objective and precise distance data were finally provided for early-type stars in the solar neighbourhood by the HIPPARCOS satellite late in 1996 (having submitted a program for the Input Catalogue, we had access to the related data 6 months before they were made publicly available in June 1997). This enabled a totally independent calibration to be made on the basis of 6044 field B- to A stars and 134 members of the Scorpio-Centaurus association. After selection over well defined parallaxes ($\pi/\sigma(\pi) \geq 5$, see Fig

Fig. 61. The residual dispersion relative to the calibration as a function of the quality of the Hipparcos parallax measurement (left). The distribution of the residual dispersion is shown on the right.



The following polynomial form, of fourth degree in X and quadratic in Y, defines the latest $M_V(X,Y)$ relation:

$$M_v(X,Y) = a_0 + a_1Y + a_2Y^2 + a_3X + a_4XY + a_5XY^2 + a_6X^2 + a_7X^2Y + a_8X^2Y^2 + a_9X^3 + a_{10}X^3Y + a_{11}X^4$$ *with*

a_0	a_1	a_2	a_3	a_4	a_5	a_6	a_7	a_8	a_9	a_{10}	a_{11}
−3.7528	−21.0189	−161.4130	5.2076	−2.5839	138.1530	−2.8463	13.2480	−29.8913	2.9365	−4.0510	−1.2997

57), their location in the X,Y diagram (Y ≥ –0.06) and discrimination against known binaries (including those detected by HIPPARCOS), 1580 stars of classes V to III remained for the calibration. These were then de-reddened by means of the intrinsic colour estimators, thus providing the reference sample of M_V. The resulting calibration is shown in Fig 60 as a 3-dimensional representation. A more detailed discussion of the calibration is given by CRAMER (1997).

(See table on page 8 - Bottom)

The residual dispersion of the M_V estimate relative to the absolute magnitude derived from the HIPPARCOS parallax after correcting for reddening is shown in Fig 61.

Here too, the standard deviation over the residuals (after subtraction of the component inherent to HIPPARCOS) amounts to 0.44 mag, and is comparable to those of the earlier calibrations. Translated into terms of distance, we observe the mean dispersion of 60 pc (hwhm) shown in Fig 62 (which includes the HIPPARCOS uncertainty) within the approximately 300 pc range of the calibration data.

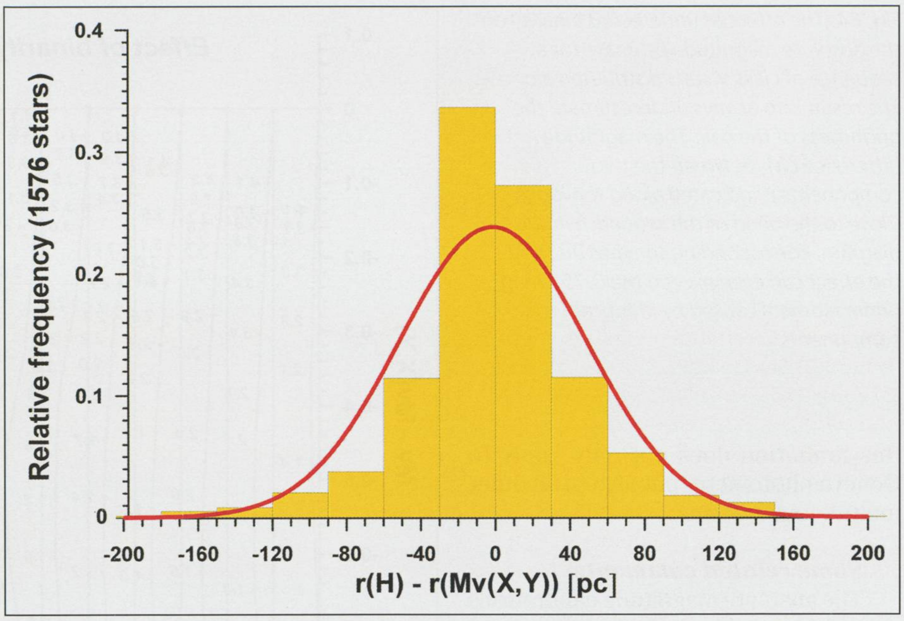


Fig. 62. Histogram of the residuals over the calibration data in terms of distance. The fitted distribution has an hwhm of 60 pc for the sample extending out to about 300 pc.

A sizeable part of these ubiquitous four tenths of a magnitude of uncertainty arises from the gradient of the calibration acting on the uncertainties over the parameters themselves. The mean *internal* standard deviation of $M_V(X,Y)$ may be estimated by the standard deviations of the X and Y parameters weighted by the total differential of the calibration function. The resulting error function is mapped into the X,Y diagram of Fig 63 with the Geneva catalogue stars as a background, and shows that an uncertainty of the order of 0.20 mag is unavoidable for purely metrological reasons. The probable internal error over the colour excess estimate can be derived in a similar manner. For $E_{[B-V]}(X,Y)$, it varies between 0.004 and 0.010 mag.

Among the underlying astrophysical causes of dispersion, rotation can be expected to contribute to dispersion by about 0.1 mag in the average (see CRAMER and MAEDER 1979). However, binarity still remains the major perturbing agent of an M_V calibration. The importance, and complexity of the binarity loops for this calibration are given in Fig 64 for main sequence stars with indication of the δM_V of the components. As already mentioned, the effects of binarity in a photometric diagram depend on the shape of the related sequence. For stars of types later than B8V (X ≥ 1.1), the variation of colour due to a bend in the lower sequence generates an error on the estimate that may even exceed the 0.753 mag that would be caused by an identical twin. Hence, the dispersion of the residuals amounting to some 0.40 mag for the various attempts to calibrate M_V should not be considered as a cause of surprise, but rather as an *inevitable* limitation of the photometric method. Finally, we may add here that

Fig. 63. Mean internal standard deviation of the $M_V(X,Y)$ calibration in the X,Y diagram, all weights considered, with 12800 stars plotted in the background. An error ranging from 0.1 mag to about 0.4 mag, depending on the local declivity of the relation, can be expected for metrological reasons alone. Uncertainties of that order are common to all ground based photometric estimates of M_V.

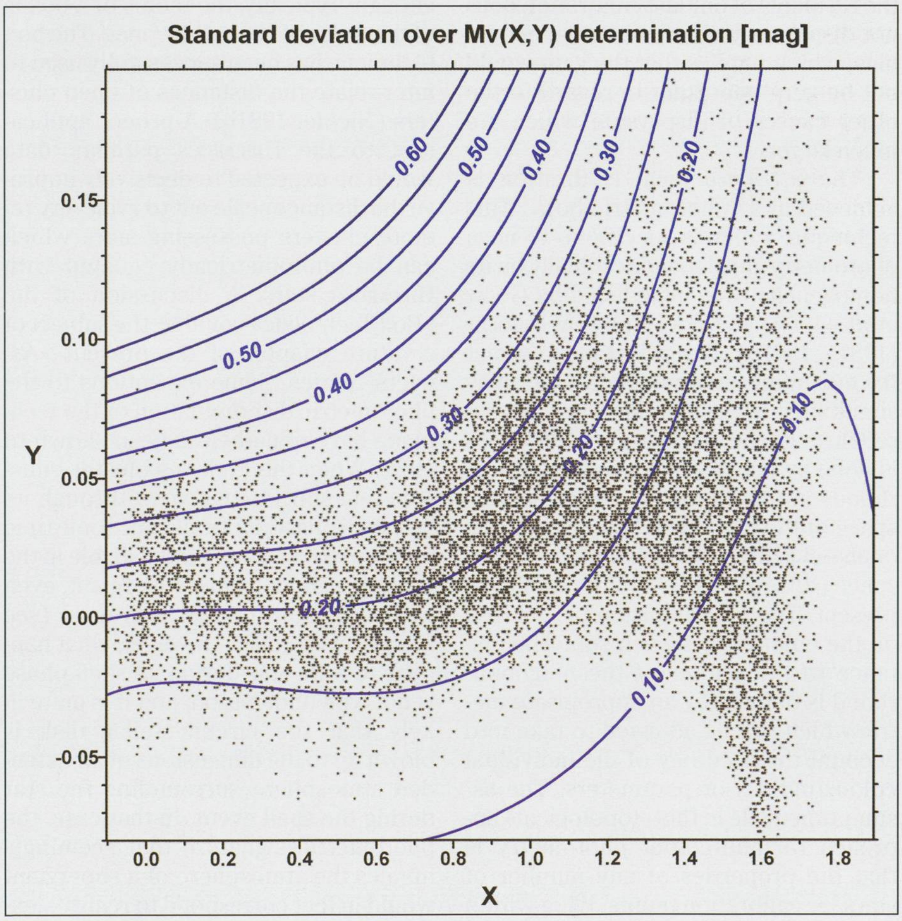
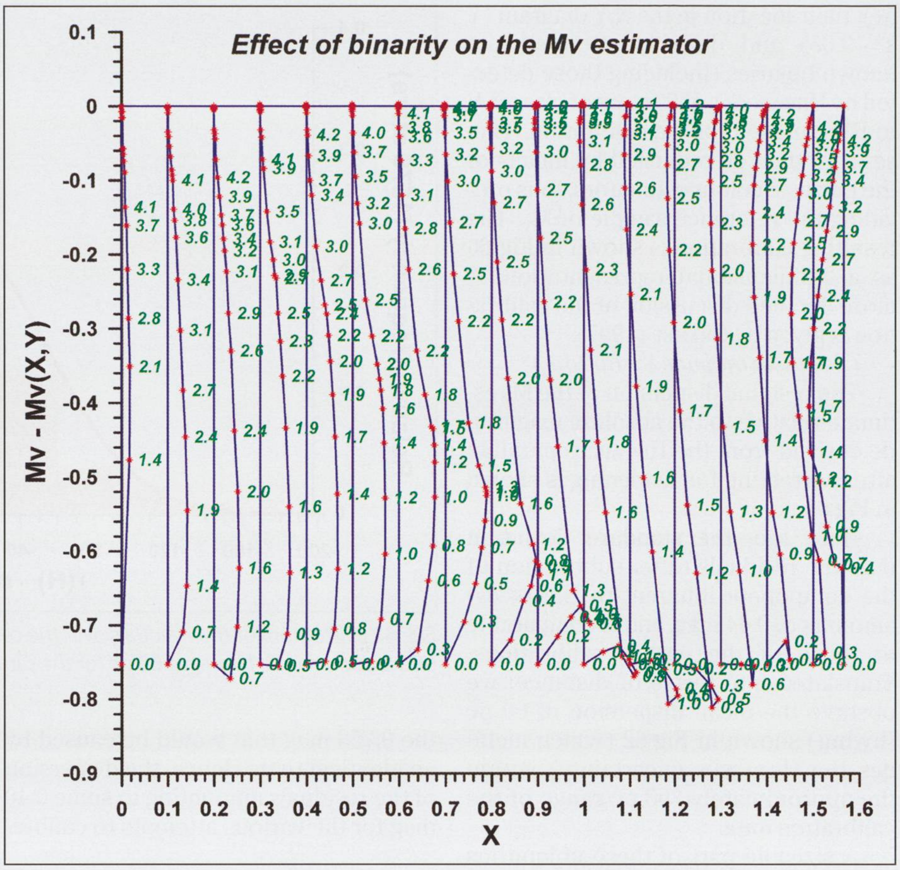


Fig. 64. The effect of undetected binarity on the absolute magnitude estimate for a sequence of class V stars distributed along X. The result is to always underestimate the brightness of the pair. The magnitude difference δM_V between the two components is indicated along the loops. Close to the bend of the sequence in the X,Y diagram, corresponding to types B8 to A0, the effect can even exceed the 0.753 mag underestimate caused by identical components.



this limitation does not only apply to Geneva photometry but also to all other multicolour systems.

Some related comments

The absolute magnitude calibrations used above, particularly the polynomial forms, are global relations which cannot promise to perfectly account for the true physical connection with M_V at all points of the validity range. Separate calibrations adjusted over smaller ranges where the colour variation gradient is more important, or where interference due to overlapping sequences can occur, may reduce the overall zero-point error (O – B1 stars, see for example appendix of RABOUD et al. (1997), or specifically A0 to A2 stars). Nevertheless, examination of the X,Y distribution of the residuals of our last calibration does not display any clear colour-dependant bias, which implies that the gain would not be very important in regard to the other causes of dispersion which are much larger.

The *ultimate* local calibration is achieved in a «photometric box». This technique, which is specific to Geneva photometry and depends critically on its homogeneity, was introduced by GOLAY et al. (1969) and developed by NICOLET (1981a, 1981b). The object is to extract the maximum amount of information by simultaneously using the values measured through the whole set of filters. This is done by considering small neighbourhoods in the six-, or less, dimensional space of the normalised colour indices, or else in a three-dimensional parameter space (d, Δ, g or X, Y, Z) if reddening is present. The neighbourhood is centred on the colours of a given star. The distance to the border of the neighbourhood is defined by an appropriate metric which can be adjusted to take into account the accuracy of the individual colour indices or parameters. The assumption made in this «topological» approach to multicolour photometry is that the properties of any number of stars, or calibration points, lying within the given neighbourhood can be equated with each-other, provided that the radius of the «photometric box» is small enough. Typically, the radius of a box is of the order of 10^{-2} to $2\ 10^{-2}$ mag. The box technique has been successfully used to inter-relate the distances of open clusters (Nicolet 1981b). A proper application to the HIPPARCOS parallax data would be expected to decisively improve the distance scale out to even very remote clusters possessing stars which can be photometrically equated with HIPPARCOS stars. A discussion of the «Box Technique» could be the subject of a future chapter of the present «Aspects» series. Some exceptions to the photometric discrimination of the technique have nonetheless been shown to exist. When the Pleiades cluster emission-line star Pleione went through its last shell phase, it became for some time photometrically indistinguishable in the Geneva system from a supergiant, even when the box method was used (see CRAMER et al. 1995). However, what happens to a Be star during its shell phase is not well understood, and it is quite likely that the circum-stellar disk is blown up to the dimensions of an extended atmosphere surrounding the star during the shell event. In that case, the photometric signature that seemingly mimics the atmosphere of a supergiant would in fact correspond to reality – except for absolute luminosity – during that short period of a few months.

A different comment may be made in regard to the correction of interstellar extinction. The HIPPARCOS parallaxes have unquestionably revealed a number of problems affecting the determination of cluster distances by using photometric sequences, notably for the Pleiades cluster mentioned above. The distance estimated for the cluster by the present calibration (which did not initially have access to Pleiades data) reproduces the classical value of 130 pc instead of the HIPPARCOS determination of 116 pc (MERMILLIOD et al. 1997). Adjustments of helium content to explain the apparently lower luminosity of its members do not work out satisfactorily (HANSEN RUIZ and VAN LEEUWEN 1997). A very peculiar reddening law with a total to selective absorption ratio R of more than twice the standard value would go in the sense of solving the discrepancy, but is unlikely to have gone undetected in view of the extent to which the cluster has been studied at all wavelengths. It now seems more probable that the HIPPARCOS data were affected in the particular case of the Pleiades bright star parallax measurements by a slight «correlation bias» inherent to the reduction method (see I. NEILL REID, 1999). If the HIPPARCOS parallaxes were, nevertheless, to be correct, the simplest explanation could be provided by the hypothetical presence of a small neutral, or almost achromatic extinction in that direction. The cluster is known to be located at the fringe of a large molecular cloud complex. The properties of extinction in the visible are not well known in such media. Indeed, to our knowledge, the absence of a weak grey component which could occasionally be present in interstellar extinction has not been definitely proven yet. It could be caused by large grains or «micro snowballs» which would have to be *very* cold so as not to be easily detected by infrared or microwave observations. Their presence on a very large scale could even bear cosmological consequences, by *increasing* the distance estimates of far-away «standard candles» and thus affecting the accuracy of determinations of the Hubble constant. But – to return to the more mundane environment of our own galactic neighbourhood – the correction of interstellar extinction through its spectrally selective nature alone has proven to perform quite satisfactory up to now, though only within current observational limits, and the discussion of neutral absorption has been neglected for lack of observational means. The question remains open. Indeed, if one were to choose among the various manners of handling the problem of neutral absorption, a method involving the very accurate knowledge of distances of reddened stars and clusters would be favoured as being one of the most direct, and that may just be what we are beginning to see if the HIPPARCOS parallaxes were to prove to be consistently correct. GAIA will tell….

An obvious application

The ability to estimate absolute magnitudes as well as colour excesses of B-type stars gives easy access to a preliminary study of the importance of interstellar extinction by dust in our galactic neighbourhood. The calibrations applied to the relevant stars of the Geneva catalogue distributed within a 6° band centred on the galactic equator generate the distance versus colour excess diagram of Fig 65.

The «reddening lines» corresponding to various extinction gradients in the sense of Fig 51 (Part 4), are also drawn in this figure. These gradients refer to a uniform distribution of dust and do not fully correspond to reality since the interstellar medium is occupied by extensive dust clouds, as seen in Fig 46 (Part 4), for example. The presence of clouds is evident in figure 65. The first of these appear in the foreground of B-type stars situated at some 390 light years (120 parsecs) from us in the galactic plane. At about 400 pc, overlapping dust clouds begin to significantly obscure our view of the Galaxy in optical wavelengths.

Up to approximately 2 Kpc, however, we do encounter substantially transparent lines of sight with a corresponding visual absorption (at 5500 Å) of about 2 10^{-4} mag pc^{-1}. That value presumably reflects the minimum large scale dust content of the inter-cloud medium. It also allows us to estimate the order of magnitude of the corresponding dust density.

In the optical region, extinction is governed by MIE scattering with an *extinction coefficient* $Q_\lambda = \sigma_\lambda/\sigma_g$ which is the ratio between the *scattering cross section* σ_λ and the *geometrical cross section* ($\sigma_g = \pi r^2$) of the particles (If the wavelength of light is comparable to the dust grain size, then $Q_\lambda \sim r/\lambda$ with r = particle radius; see λ^{-1} behaviour in Fig 28, Part 2). For typical dust grains assumed to be spherical and with radii of 0.2 µm, a simple calculation using $Q_{5500} \cong 1.5$ (at 5500 Å) yields a number density as follows:

The scattering cross section of a grain is in this case.

$$\sigma_{5500} = \pi r^2 Q_{5500} = 1.9\ 10^{-9}\ \mathrm{cm}^2$$

Now, the *optical depth* τ_λ is related to the ratio of the absorbed to non-absorbed light intensity as $I_\lambda/I_{\lambda,0} = e^{-\tau_\lambda}$. In a dust cloud of thickness s it may be expressed as

$$\tau_\lambda = \int_0^s n(s)\,\sigma_\lambda\,ds$$

where $n(s)$ is the number density of the scattering particles. If σ_λ is constant, then we have

$$\tau_\lambda = \sigma_\lambda \int_0^s n(s)\,ds = \sigma_\lambda\,N_d\,.$$

So, the dust *column density* N_d along the line of sight of a given light source is the dust optical depth divided by its scattering cross section. For absorption expressed in terms of apparent magnitude, the magnitude change a_λ is *almost identical* to the optical depth:

$$a_\lambda = m_\lambda - m_{\lambda,0} = -2.5\log_{10}(I_\lambda/I_{\lambda,0}) = -2.5\log_{10}(e^{-\tau_\lambda}) = 1.086\,\tau_\lambda$$

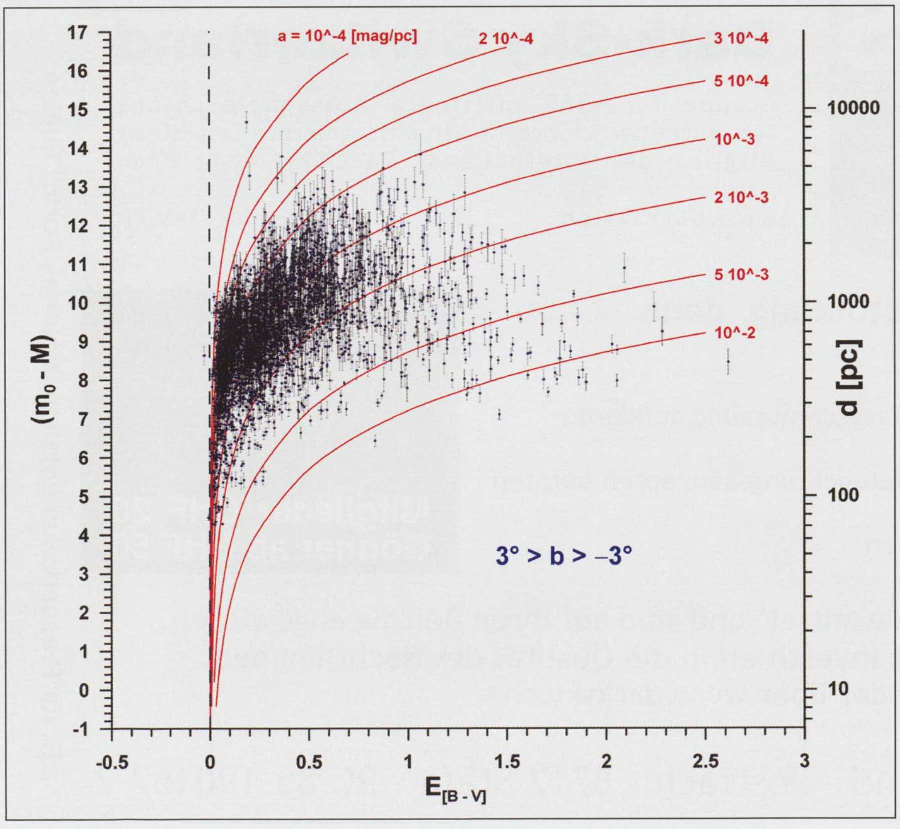


Fig. 65. The calibrations allow us to plot the true distance modulus (m_{V0}-M_V) as a function of the $E_{[B-V]}$ colour excess of stars lying along a line of sight within ± 3° of the Galactic plane. The error bars correspond to the internal standard deviations over the distance modulus and colour excess estimates. The extinction lines which would correspond to a variety of circumstances of uniform visual absorption are shown. Typical values within the first kiloparsec range between a =2 10^{-4} to 2 10^{-3} magnitudes per parsec. One also notes the first evidence of local dust clouds at about 120 parsecs.

And, with an absorption of 2 10^{-4} mag pc^{-1}, we get $\tau_{5500} = 1.84\ 10^{-4}\ pc^{-1}$, giving the column density $N_d = \tau_{5500} / \sigma_{5500} = 9.7\ 10^4\ cm^{-2}\ pc^{-1}$.

We want to express the density per volume element, so we divide by the number of centimetres in a parsec (3.0857 10^{18}), and get the average particle number density $n = 3\ 10^{-14}\ cm^{-3}$, which corresponds to a rather good vacuum occupied by only one grain per 320 m sided cube!

For a higher value of inter-cloud absorption of 2 10^{-3} mag pc^{-1} as is suggested along some lines of sight in Fig 65 we would expect number densities roughly ten times greater since the column density is almost directly related to the absorption gradient for a given grain size.

However, even though such densities may appear to be exceedingly low in the context of our everyday perception, they produce considerable screening over distances spanning thousands of light years. In clouds, dust densities can reach values that are more than 3 orders of magnitude higher. Gas (mainly hydrogen and helium) is much more abundant than dust and has particle space densities ranging from less than 0.1 cm^{-3} in the solar vicinity to about 2000 cm^{-3}, or more, in giant molecular clouds. Nevertheless, dust remains the foremost cause of interstellar extinction of light at visible wavelengths.

Finally, it is interesting to note that even serious Science Fiction authors, while recounting the travel of interstellar vessels through space at velocities of several percent that of light, do not often consider the problem of gradual damage due to the very high velocity impact of interstellar matter. One notable exception in the literature is the novel *The Songs of Distant Earth* by ARTHUR C. CLARKE (1986), where a star-ship's encounter with higher than expected gas and dust densities provides the pretext for the main story….

In the forthcoming parts of this article we will further look into interstellar dust distribution and stellar peculiarities.

NOEL CRAMER
Observatoire de Genève
Chemin des Maillettes 51, CH-1290 Sauverny

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