THE VARIABILITY OF R, N, AND C STARS FROM HIPPARCOS AND AAVSO DATA

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Abstract. Accurate photometry was obtained for all program stars during the 3.3–year HIPPARCOS mission. The final observing program included several hundred Mira (M), long-period semiregular (SR), and irregular (L) variables. A detailed calibration of the aging of the optics allowed the evaluation of very precise magnitudes over the whole range of star colors. Since the time coverage of the satellite observations was not sufficient to describe the behavior of M, SR, or L type variables, smooth curves were fitted statistically to the dense AAVSO observations. These curves were then transformed to the HIPPARCOS system in order to complement the HIPPARCOS photometry and thus produce precise light curves with fuller time coverage, for a set of several hundred late-type variables, including most carbon stars brighter than $V = 12.4$ at minimum luminosity. A preliminary discussion of the behavior of C stars, as observed from space in the broad Hp band, is given.

1. LPVs in the HIPPARCOS Program

During the compilation of the HIPPARCOS Input Catalogue (HIC), special attention was given to obtaining uniform all-sky coverage of late type

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variables, including the poorly known ones in the Southern hemisphere. The inclusion of long-period variables (LPVs) in the HIC was possible only for those brighter than HIPPARCOS magnitude $Hp = 12.5$ (the detection threshold) during at least 80 % of their cycle. One of the prerequisites of the HIPPARCOS mission was that the brightness of the targets needed to be known in advance to allocate the appropriate observing time. However, LPVs are not strictly periodic in their amplitudes, phases, and even periods. Thus the prediction of the brightness and of the observability windows (time intervals when $Hp < 12.4$) could not be achieved without performing complementary ground-based observations before and during the mission on about 340 LPVs. The responsibility of monitoring the HIPPARCOS LPVs was taken by the AAVSO, both by continuing long-term observations and adding new variables to the AAVSO observing program (Mattei 1988). About one million long-term AAVSO observations, together with about 70 000 yearly continuing observations, were used to prepare and refine the ephemerides produced by the variable star coordinator at Montpellier, France in collaboration with the AAVSO.

2. Photometric Reduction of LPVs

The main-mission photometry was performed in the wide Hp band extending from 380 to 900 nm. Due to irradiation by energetic solar and cosmic particles, the transmission of the detection chain suffered a severe wavelength-dependent deterioration during the mission. The standard Hp system was re-defined for an epoch near mid-mission. A photometric reduction to a subset of 22 000 standard stars made it possible to fix the zero point of the Hp magnitude scale to better than 0.001 mag twice per day. The very red stars were a difficult case for reduction to the standard Hp system. The reddest non-variable standards have $V{-}I$ colors less than 1.8 whereas the mean $V{-}I$ of most LPVs lies in the range from 2 to 6 mag. Note that the dominant flux for late-type carbon stars is emitted in the 700 to 900 nm domain. The early reduction algorithms were polynomial relations between the instrumental magnitudes and the standard $Hp_{\rm std}$ as a function of $B{-}V$. This approach failed to model the aging effects for late type stars, especially M and S type giants, inducing spurious long-term drifts and short-term flickering when the reduction relations were extrapolated to red variables.

The accurate definition of the chromatic aging, i.e. δHp versus $V{-}I$ as a function of time, was accomplished for red variables by forcing $Hp{-}V_{\rm AAVSO}$ to be constant, at a given light-curve phase and $V_{\rm AAVSO}$, throughout the mission. The $\delta Hp/(V{-}I)$ relation is a non-linear function of $V{-}I$. For reduction purposes, a linear pseudo-index was defined as given in Table 1.3.2

of *The Hipparcos and Tycho Catalogues* (HIP), Vol. 1 (ESA 1997). This linearization procedure is nearly exact for stars with $V\text{–}I$ less than 2, but it may leave reduction residuals of the order of a few percent on individual magnitudes.

Simultaneous observations, both visual estimates by AAVSO observers and photoelectric observations with a CCD camera and classical Geneva photometer, were performed to tie the Hp, $V_{\rm CCD}$, V_G, and V_J scales for red semiregular and Mira type LPVs. For M, S, and C stars a unique relation exists between Hp and the Johnson V_J, as a function of $V\text{–}I$. Note that M and C stars have a very distinct behavior in the $(Hp\text{–}V)/(B\text{–}V)$ or $(Hp\text{–}V_T)/(B_T\text{–}V_T)$ plane — see Fig. 1.3.7 in *The Hipparcos and Tycho Catalogues* (HIP), Vol. 1 (ESA 1997).

The adopted relation $Hp\text{–}V$ versus $V\text{–}I$ from the Cousins system is given below:

$V\text{–}I$:	2.00	2.50	3.00	3.50	4.00	4.50	5.00	5.50	6.00
$Hp\text{–}V$:	0.08	0.02	–0.09	–0.28	–0.53	–0.81	–1.10	–1.38	–1.66

3. Light Curves of Carbon Stars

All R, N, and C type stars observed by HIPPARCOS turned out to be variable — either irregular, semi-regular or nearly periodic. Since $\lambda_{\rm eff}(Hp)$ is larger than $\lambda_{\rm eff}(V)$, the amplitude in the Hp band is generally smaller than in the B and V bands. This behavior is illustrated in Figure 1 for HIP 59844, the pulsating star BH Cru.

The ratio $Q = A_{Hp}/A_V$ is around 0.7 for early type C and M giants. It shows a slight decrease for the reddest stars (Figure 2).

Large-amplitude periodic variables often show nearly sinusoidal folded light-curves, e.g. HIP 109089 in Figure 3.

A bump near phase 0.7 is present in many light curves as shown for HIP 106583, 99653 or 26753. Semi-regulars and stars pulsating in the first overtone show rather noisy folded light curves due to their varying amplitude and not-so-periodic behavior. For small-amplitude irregulars, the time coverage during the HIPPARCOS mission was sufficient to describe their behavior in terms of peak-to-peak amplitudes and time scales for variations (cf. Eyer & Grenon 1997).

The Hp amplitudes show two regimes for periodic R, N, and C variables. R stars and some C and N stars show a linear relation between the period and the amplitude which may be expressed as $A_{Hp} = 0.0013\times$Period. For the classical C-rich Miras with typical A_{Hp} in the range 1.2 to 2.4 mag, the amplitude shows little if any dependence on the period, ranging between 200 and 480 days. The global behavior is displayed in Figure 4.

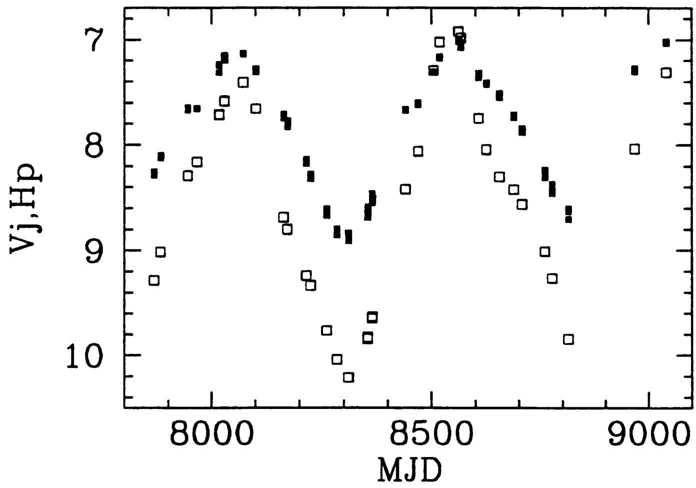

Figure 1. The light curve of BH Cru (HIP 59844), of spectral type SC 4,5-8e, in the *Hp* magnitude (*filled squares*) and in the visual *V* magnitude (*open squares*) as deduced from AAVSO observations.

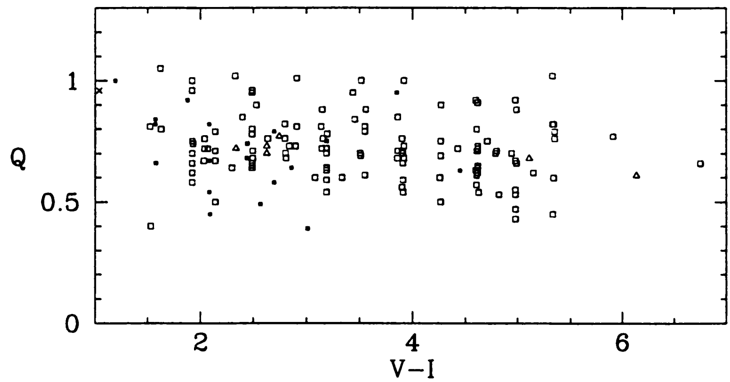

Figure 2. Q, the ratio of the *Hp* amplitude to the *V* amplitude, as a function of the *V–I* color for red variables. *Open squares*: M type; *open triangles*: S type; *filled squares*: C type; *crosses*: K and M supergiants.

4. HIPPARCOS–AAVSO Light Curves

The visual estimates are obtained by interpolating the brightness of the variable star using a set of reference stars of known magnitude in its field. The difference between the response of the eye and of the V_J band leads to an offset between the visual and the photoelectric V_J magnitude, proportional to the color difference between the comparison stars and the red variable.

The monitoring by AAVSO observers generally produces a dense time

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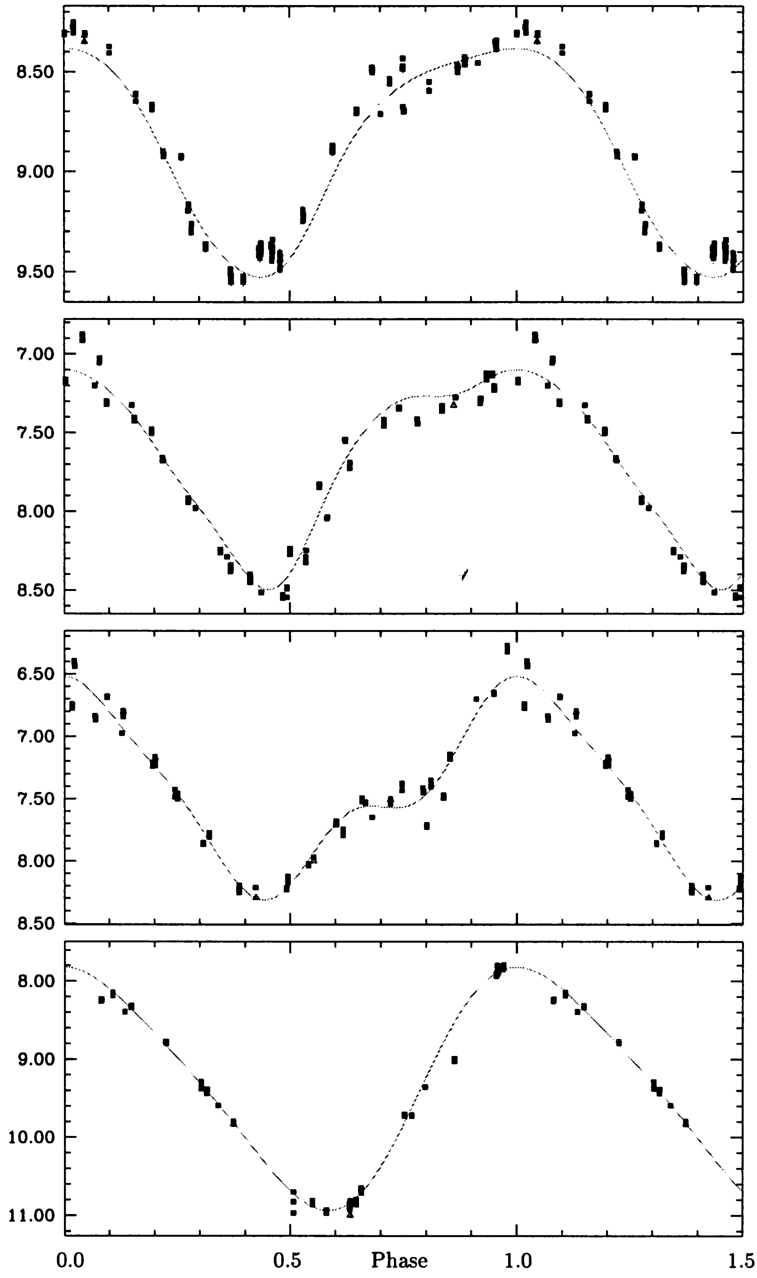

Figure 3. Folded light curves of typical C-type periodic variables monitored over 3 to 4 cycles. From top to bottom: HIP 26753, C0e, $P = 326$d; HIP 99653, C5 II, $P = 431$d; HIP 106583, C6 II, $P = 486$d; HIP 109089, C9e, $P = 436$d. Error bars are smaller than the symbol size. The dotted line is the adopted best fit used to derive the epoch and magnitudes at brightness extrema.

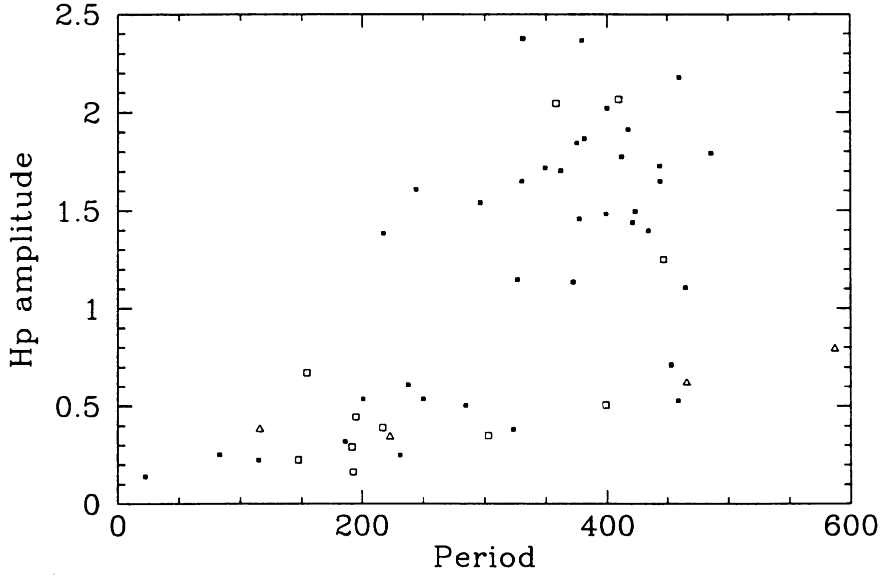

Figure 4. The relation between amplitude in Hp and period, for periodic red variables of type C (*filled squares*), N (*open squares*) and R (*open triangles*).

coverage, but because observations of different observers are combined, and because the accuracy of an individual observation is only between 0.1 and 0.3 mag, the light curves are noisy. Thus, average light curves were obtained by fitting curves to the individual observations by Fourier, polynomial or quintic spline methods. These fitted curves were then transformed to Hp magnitudes and HIPPARCOS photometry was then superimposed upon them.

The difference Hp–V is a function of the star's temperature and of the circumstellar and interstellar extinction. Since the color change as a function of the phase is generally unknown, the technique used to reduce AAVSO magnitudes to Hp was to plot $Hp - V_{\rm AAVSO}$ versus $V_{\rm AAVSO}$. For LPVs the relation is often S-shaped, as shown for the C0ev type star HIP 4284 (Figure 5).

The fine structure of Hp–$V_{\rm AAVSO}/V_{\rm AAVSO}$ diagrams depends mainly on the $T_{\rm eff}$ and $\log g$ variations and on the corresponding absorption changes due to TiO, VO or CN, C_2, SiC_2 molecular bands. Emission lines and dust extinction introduce departures from the mean relation.

Although distinct relations seem to exist for the rising and falling parts of the light curve, a unique third-degree polynomial was used to transform fitted AAVSO magnitudes to Hp magnitudes with an uncertainty of 0.1 to 0.2 mag in most cases. This uncertainty is generally small compared to the peak-to-peak Hp amplitude. Errors in comparison-star magnitudes are

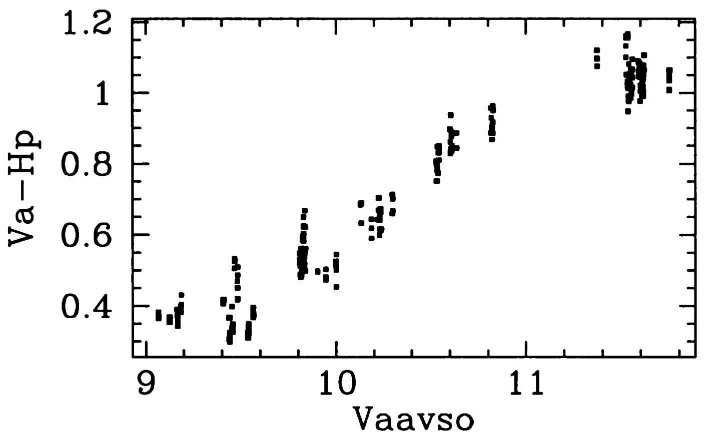

Figure 5. Example of the non-linear relation V_{AAVSO}–Hp *vs.* V_{AAVSO} used to transform visual light curves into Hp light curves.

automatically corrected by this process.

The Atlas of HIPPARCOS–AAVSO light curves, part B (ESA 1997), contains 274 stars in common. Here we show a few representative cases of C-star light curves which would be difficult to interpret with HIPPARCOS data alone. This is especially true for the RCB variable RY Sgr, where the main minima were missed due to the peculiar HIPPARCOS time sampling, and the semiregular variable V Hya, which has periods of 530 days and over 6000 days, and where HIPPARCOS observations were obtained while the star was slowly fading to the minimum of its longer period (see Figure 6).

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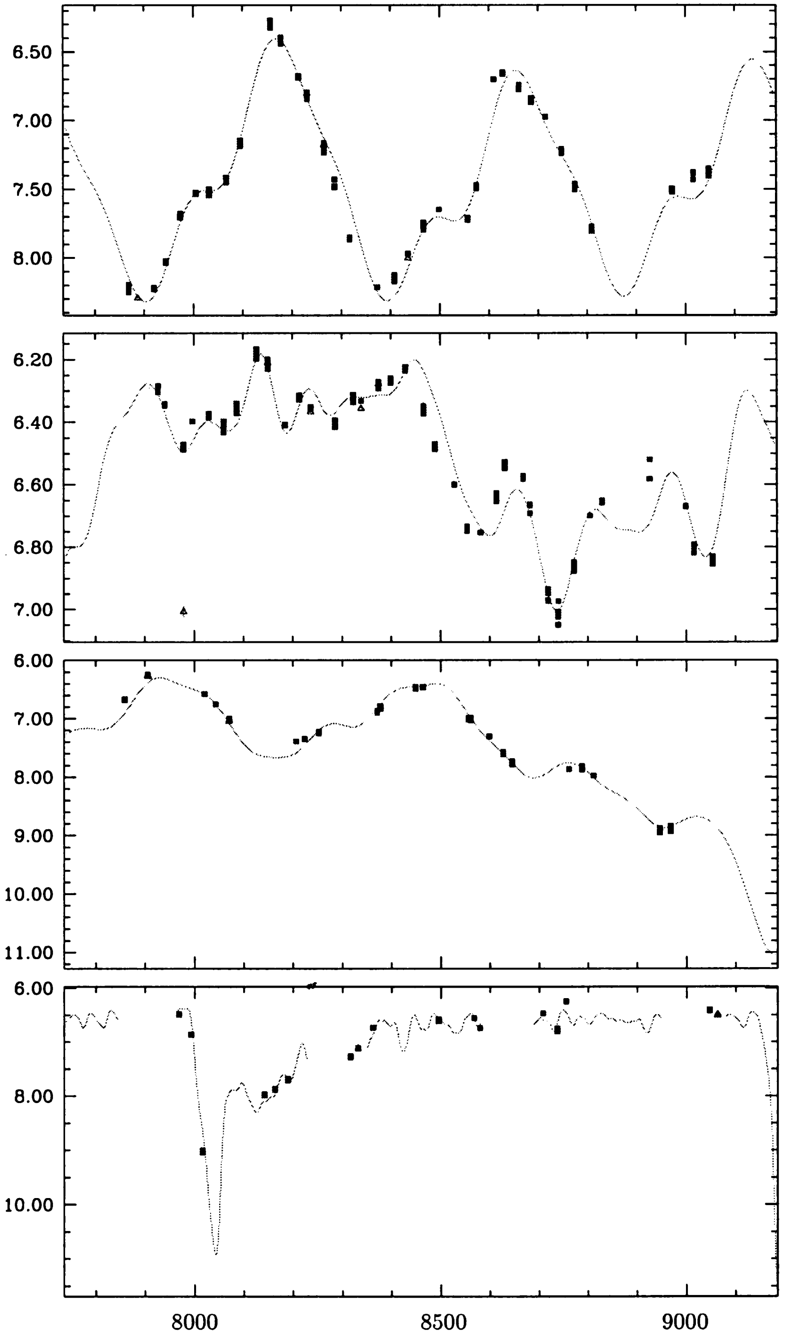

Figure 6. Light curves of C-type Mira and semiregular variables. From top to bottom: HIP 106583, C6 II, S Cep; HIP 63152, C7 I, RY Dra; HIP 53085, C9 I, V Hya; and HIP 94730, Cp, RY Sgr, an RCB variable. Error bars are smaller than the symbol size.

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