BLUE VARIABLE STARS FROM THE MACHO DATABASE. I. PHOTOMETRY AND SPECTROSCOPY OF THE LARGE MAGELLANIC CLOUD SAMPLE

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ABSTRACT

We present the photometric properties of 1279 blue variable stars within the Large Magellanic Cloud. Photometry is derived from the MACHO database. The light curves of the sample exhibit a variety of quasi-periodic and aperiodic outburst behavior. A characteristic feature of the photometric variation is that the objects are reddest when at maximum outburst. A subset of 102 objects were examined spectroscopically. Within this subset, 91% exhibited Balmer emission in at least one epoch, in some cases with spectacular spectral variability. The variability observed in the sample is consistent with the establishment and maintenance of the Be phenomenon.

Key words: galaxies: individual (Large Magellanic Cloud) — stars: emission-line, Be — stars: variables: other

On-line material: machine-readable table

1. INTRODUCTION

The MACHO photometric database constitutes an unprecedented resource for the study of stellar variability. With coverage of over 20 million stars within the Large Magellanic Cloud (LMC) alone, the MACHO project is superior to competitors in duration (7 years) and spatial coverage. A primary goal of the MACHO project was to detect microlensing events in or toward the Magellanic Clouds and the bulge of the Galaxy. Among the initial unexpected contaminants in the detection of microlensing events were blue variables provisionally termed “bumpers” (Cook et al. 1995). These objects were found to brighten $D_V = 0.2$–0.4 mag over the course of 50 to several hundred days in a manner much like that expected from microlensing events. However, these objects did not exhibit the achromaticity expected of microlensing.

In the present work we extract from the catalog of MACHO variables (over 210,000 objects) those stars that are in the vicinity of the main sequence and exhibit large amplitude variability (see §2). Section 3 presents an overview of light curve morphology and color variations. Section 4 presents spectroscopic observations of a subset of 102 objects from our catalog. In §5 we discuss the physical nature of the blue variables. The goal of the current paper is to present preliminary data on these objects for future studies to expand upon.

2. SELECTION OF THE SAMPLE

Instrumental MACHO $B$ and $R$ magnitudes have been transformed to standard Johnson $V$ and Cousins $R$ (for details see Alcock et al. 1999). From this database we have selected blue (i.e., $-0.5 < V - R < 0.4$) objects with $V < 18.0$. We then selected those stars with significant variability. Our variability index borrows from that used to detect MACHO microlensing events (Alcock et al. 1995). Under this scheme, a star is flagged as variable if the light curve contains at least 10 pairs of $V$ and $R$ of large $\chi^2$ compared with a constant $V$ and $R$ brightness. From the 30 LMC MACHO fields with calibrated photometry this results in a sample of 2841 candidate variables. Eclipsing binaries, that were excluded by visual inspection, were a major contaminant. This results in a sample of 1279 objects. The positions, magnitudes, and colors of these objects are presented in Table 1.

3. PHOTOMETRY

Our selected blue variables show a remarkable variety of light curve morphology. To attempt to classify each star into a series of arbitrary categories is perhaps misleading as stars may show combinations of what might be termed “modes” of variability. These “modes” can be described as follows:
1. Bumper events—these events are typically $\Delta V = 0.2$–0.4 mag in amplitude and duration of 100–800 days.

2. Flicker events—rapid, generally low-amplitude ($\Delta V = 0.05$–0.15 mag) variation. Duration of outburst ranges from 10 to 50 days. Rise time is very short (several days) followed by exponential decay. Larger outbursts result in longer durations. Flickering behavior is often associated with maximum light of bumper modes (Fig. 2).

3. Step events—within the course of 10–50 days the brightness increases; $\Delta V = 0.2$–0.3 mag.

4. Baseline variation—long-term trend of thousands of days with amplitudes up to $\Delta V = 0.4$ mag.

5. Fading events—drop in $V$ luminosity of up to $\Delta V = 0.4$ mag with timescales 200–600 days.

Figure 1 shows examples of these modes. As can be seen from Figure 2 many stars exhibit modes 1–5 in combination. The $V−R$ colors show that outburst events result in redder colors. While modes 1, 2, and 5 bring about a simultaneous change in color, modes 3 and 4 often exhibit a long delay (~1000 days) between attaining maximum light and attaining reddest color.

The seven-year baseline of the MACHO photometry shows the ephemeral nature of each mode. A particular mode of behavior may switch on or off without precursor. For this reason we propose that the five modes of variability are expressions of one underlying mechanism, which we discuss below. In a small number of our sample (324 of 1279 stars) the variability appears quasi-periodic albeit with variable amplitude. Among quasi-periodic stars, periods range from 150 to 1400 days for mode 1 with a mean period of 560 days to 20–100 days for objects of mode 2 (mean $P = 65$ days).

Figure 3 shows the $V$, $V−R$ color-magnitude diagram for the sample of blue variables we have isolated. These stars form a broad band parallel to the nonvariable stars on the main sequence. This red offset is of similar magnitude to...
that observed among the Magellanic Cloud Be star population (Keller, Wood, & Bessell 1999). Shown in large symbols are those objects that exhibit only one mode in the available data. The five modes inhabit a similar range in color. Figure 4 presents the luminosity functions for the subset of single-mode stars. At high luminosity, large outburst behavior (mode 1) dominates the blue variable population. The smaller mode 2 events are significantly skewed to lower luminosities.

4. SPECTROSCOPY

Spectroscopy was performed on a subset of 102 blue variables. These observations were conducted on eight epochs; however, only 39 stars have two or more observations. Table 2 describes our spectroscopic observations. The sample of objects observed spectroscopically contains stars from each of the five modes discussed above.

Among the stars in our sample, 91% show Balmer line emission in at least one epoch. That is, the majority of objects are Be stars. Given the fact that such a high proportion of the sample show emission in our limited number of epochs and the variable nature of the emission-line phenomenon, it is highly likely that all stars in our sample are Be stars. Among the 39 stars with multiple spectroscopic observations ~50% show dramatic variation in emission equivalent width of H Balmer lines. The most variable are those that undergo outburst from a quiescent constant baseline. An example of this extreme variability is shown for three

![Fig. 3.—$V$, $V-R$ color-magnitude diagram for the blue variables described in the present work, showing mode 1 (filled squares), mode 2 (stars), mode 3 (open squares), mode 4 (asterisks), and mode 5 (circles). The zero-age main sequence is shown for comparison (Balona & Shobbrook 1984).](image)

![Fig. 4.—Luminosity functions of those stars exhibiting only one mode of variability over the duration of our monitoring, showing mode 1 (dashed line), mode 2 (solid line), mode 4 (dotted line), and mode 5 (dash-dotted line). Mode 4 is not shown as it is represented by a very small population.](image)

**TABLE 2**

Details of Our Spectroscopic Observations

| Date       | MJD   | Instrument          | Wavelength Coverage (Å) | Resolution $\Delta \lambda$ (Å) |
|------------|-------|---------------------|-------------------------|----------------------------------|
| Dec 30 1994| 49717 | AAT/RGO             | 6290–6840               | 1.0                              |
| Jan 2 1997 | 50451 | CTIO 60 inch        | 3640–7330               | 4.4                              |
| Nov 26 1998| 51144 | SSO 2.3 m/DBS       | 3600–4580; 6095–7050    | 1.1; 1.1                         |
| Mar 28 1999| 51266 | SSO 2.3 m/DBS       | 3315–5500; 5500–10200   | 4.4; 8.0                         |
| Sep 22 1999| 51444 | SSO 2.3 m/DBS       | 3250–6410; 6400–10400   | 4.4; 8.0                         |
| Dec 12 1999| 51525 | SSO 2.3 m/DBS       | 3600–4600; 6100–7050    | 1.1; 1.1                         |
| Dec 2 2001 | 52246 | SSO 2.3 m/DBS       | 3610–4590; 6090–7045    | 1.1; 1.1                         |
| Mar 4 2002 | 52310 | SSO 2.3 m/DBS       | 3610–4590; 6090–7045    | 1.1; 1.1                         |
stars in Figure 5. The Hα line profile is seen to vary from absorption to equivalent widths of over ~60 Å. The time of maximum light is associated with maximum Balmer line emission in each instance. Those that do not exhibit a constant baseline are characterized by strong emission (typically ~20 to ~40 Å).

5. NATURE OF BLUE VARIABLES

The blue variables of the LMC exhibit a variety of light curve morphology, yet present similar color, luminosity distribution, and spectral types. We believe that the lack of differences between objects exhibiting different modes is due to the fact that the variability has a common underlying mechanism. The Be phenomenon (and the process underlying it) is the prime suspect for the production of the variability. A Be star is defined simply as a B star that has at one time exhibited Balmer emission. We find that 91% of the blue variable population examined spectroscopically are Be stars.

An early reference to the unusual population of blue variables in the LMC was made by Hodge (1961), who discussed a class of variable stars that matched that outlined here, namely, stars to the red of the main sequence presenting eruptive outbursts that are redder when brighter. Subsequently, the EROS microlensing survey has also discussed the blue variable population in the LMC (Beaulieu et al. 1996; Lamers, Beaulieu, & de Wit 1999). These studies highlighted a small sample of seven objects that satisfy selection criteria similar to those applied here. These studies claim, however, that the blue variables belong to a pre–main-sequence population analogous to Galactic Herbig Ae/Be stars. Study of the EROS Small Megallanic Cloud data by Beaulieu et al. (2001) and de Wit, Beaulieu, & Lamers (2002) reveals a further seven similar objects.

Five of the seven EROS LMC objects are present within our catalog of blue variables. The counterparts of two objects are not present because they do not exhibit significant variability in our data set. Seen in the context of our eight-year baseline rather than the limited 117 days of EROS, these objects do not show variability, which sets them apart from the remainder of our sample.

Figure 6 presents the light curves for ELHC 1, 2, 3, and 6 (ELHC 5 was observed in MACHO R band only but is clearly of mode 1). The variability exhibited is distinct from the frequent, large-amplitude (up to 3 mag) fading events of short duration (2–50 days) seen in Galactic Herbig Ae/Be
Fig. 6.—$V$ light curves and $V-R$ color curves for four pre-main-sequence candidates identified by Lamers, Beaulieu, & de Wit (1999). Top to bottom: MACHO identifications are 78.6101.55, 78.6220.76, 79.5863.73, and 78.6100.111. Our eight-year baseline shows that these objects do not present variations of significantly different nature from those presented in Figs. 1 and 2.

stars (Rostopchina & Grinin 2001; Bibo & The 1991; The 1994). To definitively distinguish between the possible Be and Herbig Ae/Be nature of these objects will require further study, particularly infrared spectroscopy.

We propose that the variability of these stars is the result of processes related to the establishment, maintenance, and dissipation of the Be disk. The emission that characterizes Be stars originates in a gaseous circumstellar quasi-Keplerian disk. No definitive model has been developed that can sufficiently describe the formation and maintenance of this disk material. The wind-compressed disk model (Bjorkman & Cassinelli 1993) utilizes the combination of fast photospheric rotation with large mass-loss rates to generate a confined disk of material but fails short of generating the densities observed within Be star disks. Other models such as the “one-armed” density wave model (Okazaki 1997) seek to explain spectral line variations observed in Be stars.

An insight into the establishment of Be disks is provided by the works of Rivinius et al. (1998, 2001) in their detailed study of the Be star $\mu$ Cen. These authors find evidence for nonradial pulsation modes within the star that in constructive interference provide sufficient mechanical work to expel material from the stellar surface. Such material gives rise to short-lived spectral variations that damp as the material melds into the bulk of the Keplerian disk. The outbursts on $\mu$ Cen have remained of low intensity and result in only minor modulation of the $V$ luminosity.

A large proportion of galactic Be stars are known to exhibit photometric and spectroscopic variability. Many studies exist in the literature that have sought to characterize the nature of these variations (Feinstein & Marraco 1979; Dachs 1982; Hubert & Floquet 1998). The study by Hubert & Floquet of $Hipparcos$ photometry of 289 Be stars shows that among early-type Be stars variability greater than 0.02 mag (in the broadband $Hipparcos$ photometric system) is commonplace (98% among B0–B3 stars). Hubert & Floquet describe five types of variability that encompass those defined for the present sample. Short-term variations (hours to days) are low amplitude (a few hundredths of a magnitude) and are frequently periodic in nature. Midterm variations (days to weeks) are seen to occur as outbursts of several tenths of a magnitude, which are both short-lived (~50 days: e.g., $\omega$ CMa, like mode 2) and long-lived (~500 days: e.g., $\nu$ Cyg, like mode 1), and in the form of fading events. Long-term variations (years) of up to 0.12 mag are seen over the 1200 day $Hipparcos$ time span.

The photometric behavior of Galactic Be stars as described by Hubert & Floquet mimics that seen among the present sample. In particular the bumper and flicker outburst modes are of similar duration and amplitude. While the present sample of blue variables is undoubtedly heterogeneous we believe that the variability of the majority of objects can be best understood in connection with the Be phenomenon.

Let us now interpret our observations in terms of the Be phenomenon. Our spectroscopy indicates that objects exhibiting mode 1 or 2 outbursts from a flat or quiescent baseline exhibit maximum line emission when in outburst and an absence of emission when in quiescence. Each outburst event can be clearly interpreted as a mass-ejection event from the stellar surface. The ejection of material into the circumstellar environment creates a rise in luminosity and redder color due to the addition of Balmer continuum emission from the cooler disk component (Zorec & Briot 1991). A slow decline follows the initial outburst as material is removed from the circumstellar environment because of outflow (see Rivinius et al. 2001). In this proposed scenario, mode 1 and 2 outbursts arise from the same mechanism; however, in mode 1 more substantial mass loss occurs. Outbursts may also occur in systems with established circumstellar material, leading to the variety of light curve morphology seen in Figure 2. Similarly, fading events (mode 5) reflect the reduction of circumstellar material. Unfortunately we do not have multiepoch spectroscopic observations during a fading event to confirm this.

The blue variables we have presented in this work afford an excellent probe into the mechanisms of establishment and maintenance of the Be phenomenon. Further study of the combined photometric and spectroscopic variations may infer the mechanisms responsible for mass ejection and establishment of the circumstellar disk.

6. SUMMARY

We have presented a summary of the properties of 1279 blue variables within the Large Magellanic Cloud. Variations of up to $\Delta V \sim 0.4$ mag are observed in the form of rapid (~50 days) or prolonged (100–500 days) eruptive events, as well as fading events and long-term (years) trends. The $V-R$ colors show a characteristic “redder when brighter” behavior.

A subset of 102 stars were examined spectroscopically in a limited number of instances over multiple epochs. Many objects show spectacular photometric and spectroscopic variability. The majority (91%) of the spectroscopic sample were found to exhibit Balmer emission lines in at least one epoch (i.e., Be stars).
This strongly suggests that the mechanism giving rise to the variability seen in the sample of LMC stars is related to the Be phenomenon. First, the photometric variability is similar to that observed in Galactic Be stars. Second, emission strength is seen to coincide with redder $V-R$ color and maximum $V$ luminosity as expected from known properties of Galactic Be stars.

The outbursts observed in the blue variable population can therefore be understood as mass-eject events from the central star, leading to the establishment and maintenance of the Be disk. Thorough further study of this population could yield important insight into the physical process of mass loss and the confinement of material in the vicinity of stars, which underlies the Be star phenomenon. The role of metallicity in the Be phenomenon will be examined in a future paper in which we plan to investigate properties of the blue variable population of the Small Magellanic Cloud.

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