UCRL-ID- 122897

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December 13, 1995

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Work performed under the auspices of the U.S. Department of Energy by the Lawrence Livermore National Laboratory under Contract W-7405-Eng-48.

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Prepared in partial fulfillment of the requirements of the Science and Engineering Research Semester under the direction of Kem Cook, Research Mentor, in the Lawrence Livermore National Laboratory.

* This research was supported in part by an appointment to the U.S. Department of Energy Science and Engineering Research Semester (hereinafter called SERS) program administered by LLNL under Contract W-7405-Eng-48 with Lawrence Livermore National Laboratory.

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Abstract

The MACHO Project database was searched for aperiodic blue variables in the LMC. Of approximately 250,000 bright blue stars in the region of observation, around 3500 had been flagged as variables or as rejected gravitational microlensing candidates. From a visual inspection of this set, about 400 stars were selected for the catalog. These stars have been categorized by their light curve morphology. Their spatial distribution is presented and correlated with known phenomena.

Analysis of the catalog stars has produced some interesting discoveries. Among some of these variables, unusual color changes were found. Some stars become redder or do not change color when their brightness increases, whereas most stars become bluer if they rapidly brighten. For some stars with relatively long quiescent stages, the light curves were searched for low-level, periodic variability, but no conclusive evidence for such behavior was found.

1 Introduction

MAssive Compact Halo Objects (MACHOs) may account for a significant amount of the dark matter in the Milky Way. Finding these MACHOs and determining how much they contribute to the mass of the galaxy is the primary goal of the MACHO Project. Millions of stars in the Large Magellanic Cloud (LMC), Small Magellanic Cloud, and the bulge of the Milky Way are being monitored to detect gravitational microlensing events caused by MACHOs. The nightly monitoring of these stars has also created an excellent database for variable star research.

When a MACHO passes near the line of sight to a background star, the MACHO's gravitational field acts as a lens. As a result, two images of the source star appear; however, these often cannot be resolved independently since the separation is less than a milliarcsecond for a halo object mass of less than thousands of solar masses. Thus, the effect is a transient brightening called gravitational microlensing. The transient nature of the phenomenon is due to the relative motions of the source star, the MACHO, and the solar system. The brightening is achromatic and is expected to be symmetrical because the apparent motions of the components are constant over the time span of the event.

The MACHO Project nightly monitors millions of stars in an effort to detect microlensing events. The resulting database provides a vast amount of variable star data to be explored. In this paper, we present a catalog of about 400 LMC aperiodic blue variables selected from the approximately 250,000 bright blue stars in the region of observation.

The catalog stars have been classified by their light curve morphology. For example, some of the light curves are relatively constant with one to a few episodes of brightening (bumpers), some are constant with sections of "flickering," and some have step-like changes (steppers).

Preliminary analysis of the catalog stars produced some interesting information. Some unusual color changes were discovered for the bumpers and steppers. In particular, bumpers become redder when their brightness increases, and steppers do not appear to change color. For the bumpers which have relatively long quiescent stages, some of the light curves were searched for low-level, periodic variability, but no conclusive evidence for such behavior was found.

2 Procedures

The MACHO project has the dedicated use of the 1.27m Great Melbourne telescope at Mount Stromlo, Australia. Every night, fields of the LMC, or sometimes the bulge of the Milky Way and the Small Magellanic Cloud, are observed; a beam splitter allows two passbands of CCD data to be collected simultaneously. The V_{MACHO} passband is $440 - 590$ nm, and the R_{MACHO} passband is $590 - 790$ nm.

Most of the catalog was produced by selecting stars which had been flagged as potential microlensing candidates; their light curves triggered a microlens filter and could be moderately well fit by a microlensing curve. From the set of 3991 potential microlensing events, the light curves of the 561 stars that were bright (14.0 mag $< V_{MACHO} <$ 18.0 mag) and blue ($V_{MACHO} - R_{MACHO} < 0.3$) were inspected visually, and those that appeared to be aperiodic variables (382) were selected. Eighteen aperiodic blue stars were also selected from around 3000 bright blue stars which had been flagged as variable (but had not necessarily been flagged as microlensing candidates).

The stars in the catalog were visually inspected and classified according to their light curve morphology. The categories were: stars with one to a few prominent "bumps" (called bumpers, with constant or variable baseline), "flickering" stars (where the flickering starts from the baseline or on a plateau), stars with flat plateaus, and stars with step-like changes in their light curves (called steppers).

Several types of preliminary analysis were accomplished. Light curves of the color ratios were made for representatives of each group. The catalog stars were correlated with known phenomena, using the SIMBAD database.

For the bumpers with long quiescent stages, 20 randomly selected light curves were searched for low-level, periodic variations of 0.1 to 30 days, using a C program that attempts to phase the data to periods within the given interval using a supersmoother fit (Friedman 1984). In addition, the supersmoother fit was subracted out of the data for each, and the residuals were phased with the same program.

3 Data

The light curves of the catalog stars were classified according to their light curve morphology. It should be noted that these categories are only a preliminary attempt to classify the stars in the catalog. In some cases, the boundaries between categories are indefinite, and the categorization is subjective. The categories are as follows:

(1) **Sporadic bumpers with constant baseline.** These are characterized by having long periods of quiescence with occasional episodes of rapid brightening, followed by a slower decline to the previous level. The magnitude of these stars increase by about 20-40%. The rise takes place over a span of 10-20 days, with the entire "bump" episode usually lasting on the order of 100 days (see Fig. 1).

(2) **Sporadic bumpers with variable baseline.** These stars are much the same as the bumpers described above, but their baselines are variable (see Fig. 2).

(3) **Flickering stars with constant baseline.** These stars have episodes of rapid variation and stages of quiescence. The baseline during "flickering" is the same as the baseline during quiescence (see Fig. 3). The episodes of flickering may last hundreds of days, while the individual cycles of rise and decline are on the order of 10-20 days.

(4) **Flickering stars with plateau baseline.** These are much the same as the above flickering stars, but the baseline during an episode of flickering is 20-40% brighter than the baseline during quiescence (see Fig. 4).

(5) **Stars with long plateaus.** The light curves of these stars are characterized by long spans of increased but relatively constant magnitude. These stages of increased magnitude, about 20-40% above the baseline, generally last for about 100-200 days (see Fig. 5).

(6) **Steppers.** These stars are characterized by long periods of quiescence punctuated by abrupt changes in magnitude. The magnitude increases by 30-50% and is constant before and after the change, which usually occurs over a span of less than 20 days (see Fig. 6).

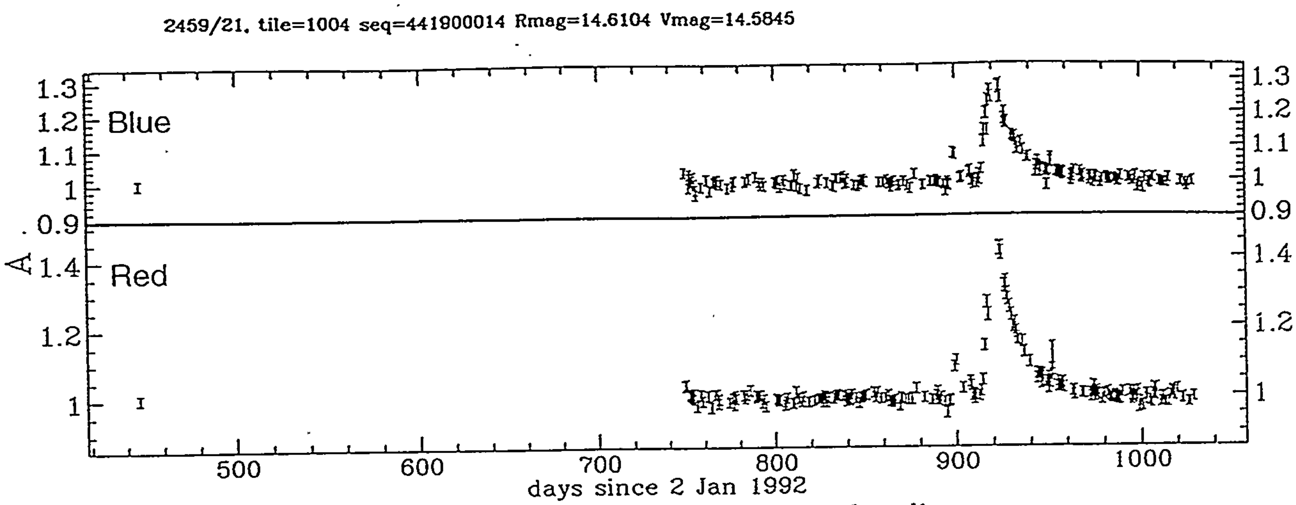

Fig. 1. Light curve of a sporadic bumper with constant baseline.

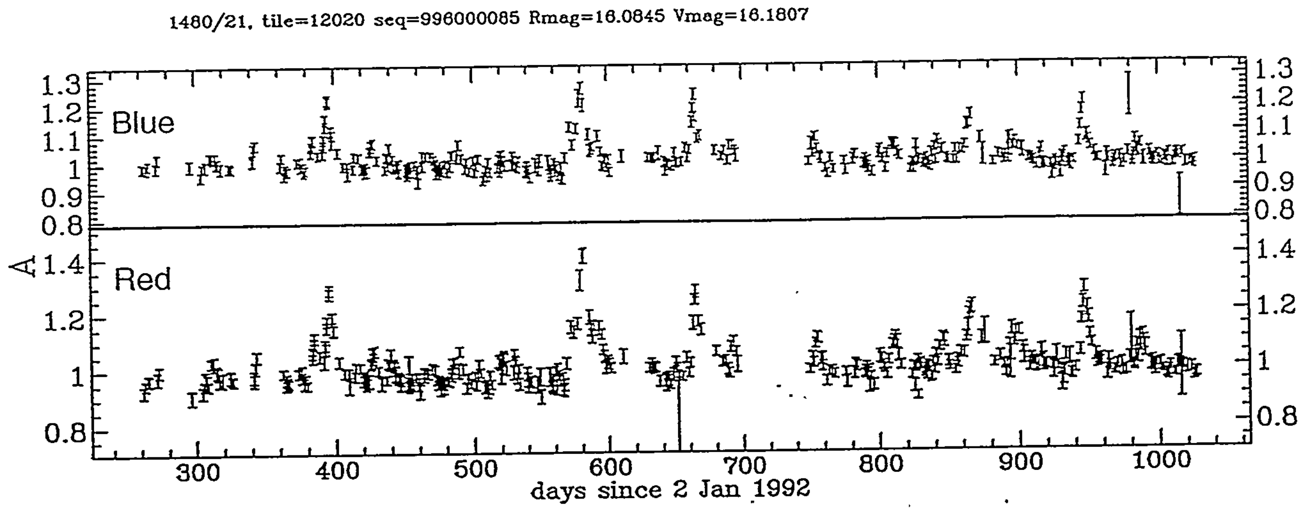

Fig. 2. Light curve of a sporadic bumper with variable baseline.

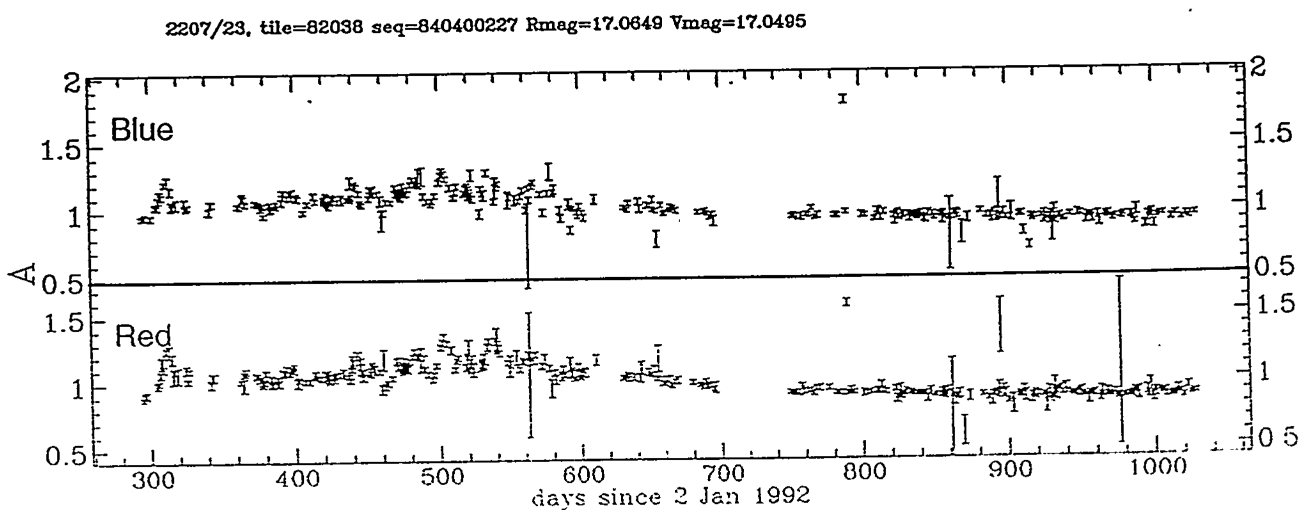

Fig. 3. Light curve of a flickering star with constant baseline.

2350/21, tile=82044 seq=912800087 Rmag=15.993 Vmag=16.0978

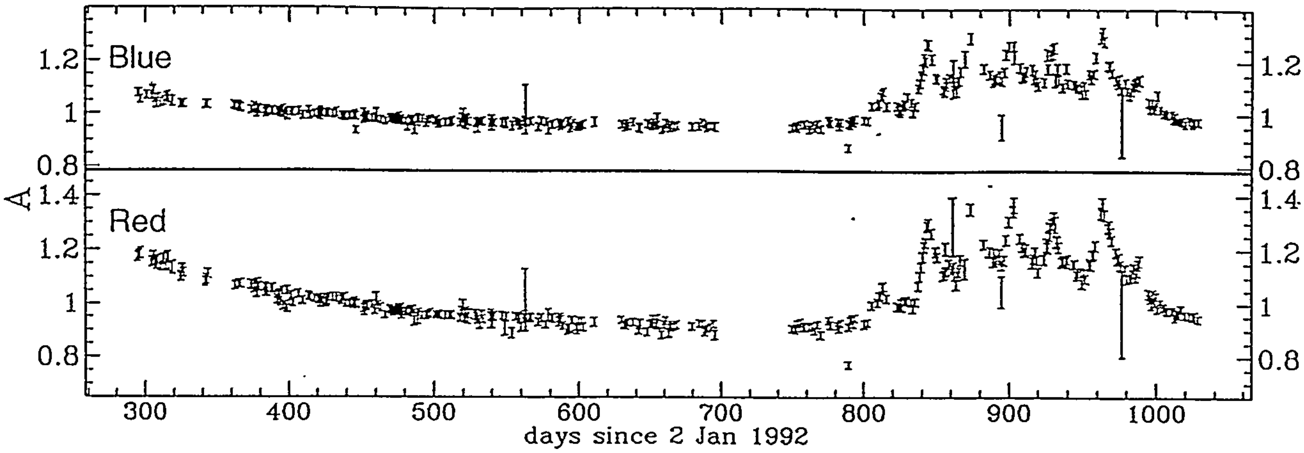

Fig. 4. Light curve of a flickering star with plateau baseline.

792/23, tile=3021 seq=648200061 Rmag=16.2275 Vmag=16.2772

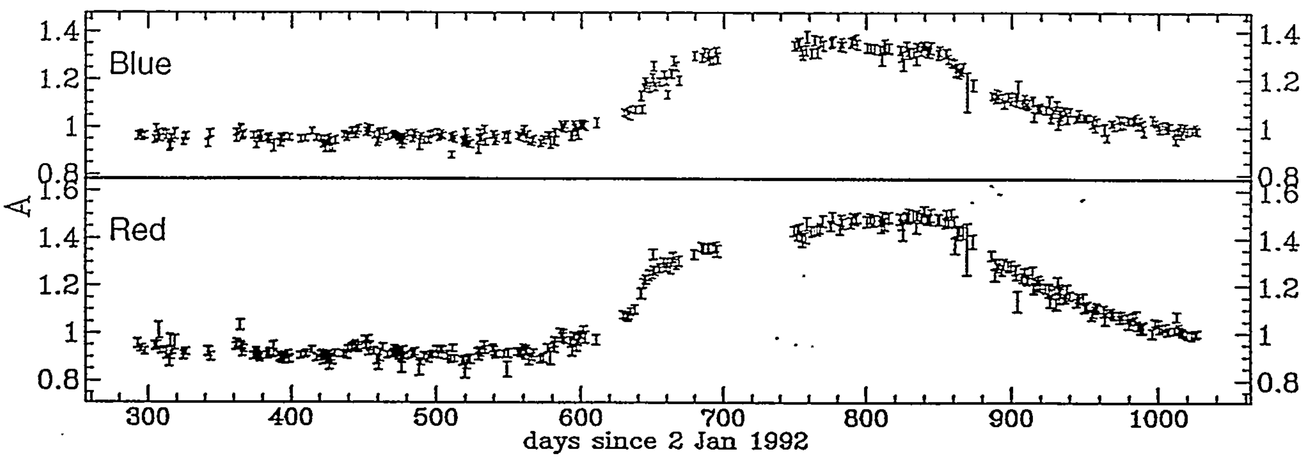

Fig. 5. Light curve of a star with long plateau.

1583/21, tile=14009 seq=850000382 Rmag=15.3618 Vmag=15.4258

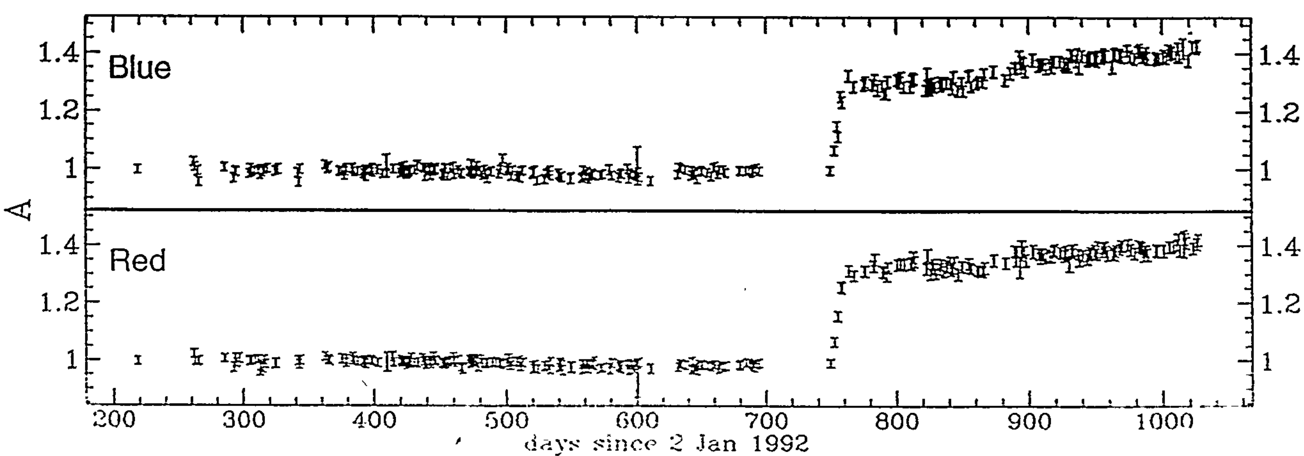

Fig. 6. Light curve of a stepper.

Not all of the stars in the catalog fall into one of these categories, and some display very unusual behavior. For example, the light curve in Fig. 7 appears similar to that of some eclipsing binaries, but the period is not entirely regular. Another example is shown in Fig. 8; here, the star varied with a regular period and with an overall downward trend, then it stopped varying and became constant. Additional data shows that this star later resumes its variations, this time with an upward trend.

Currently, attempts are being made to correlate the catalog stars with known phenomena, as listed in the SIMBAD database. There is an interesting correlation with supernova 1987A. Several objects, which form a ring around 1987A, show dramatic increases in magnitude around 1000 days (late September 1994). Since the correlation process is still in progress, there is little more to report at this time.

About 20 bumpers with constant baselines were tested for low-level periodic variability. When the results of the first tests were inconclusive, the data were fit by a supersmoother curve. This was then subtracted out of the data, and the residuals were phased. No conclusive evidence for low-level periodic behavior was found. An example of a typical result from the phasing program is shown in Fig. 9.

Representatives of each of the categories of catalog stars were selected and their color light curves plotted. Many of the steppers displayed little or no color change during the change in magnitude (see Fig. 10). Most of the bumpers became redder during "bumps" (see Fig. 11).

4 Discussion

The primary result of this project is the compilation of a catalog of aperiodic blue variables in the LMC. In the course of accomplishing this, some unusual and very distinctive light curves were discovered. Many of these are quite different from any previously studied stars and are in need of further study; the two stars whose light curves are shown in Fig. 7 and Fig. 8 are examples of this.

Another discovery involves the color changes of some of the catalog stars. When most variable stars brighten rapidly, they become hotter and bluer. Bumpers, however, are unusual in that they seem to become redder when their brightness increases. This would mean that their temperature drops

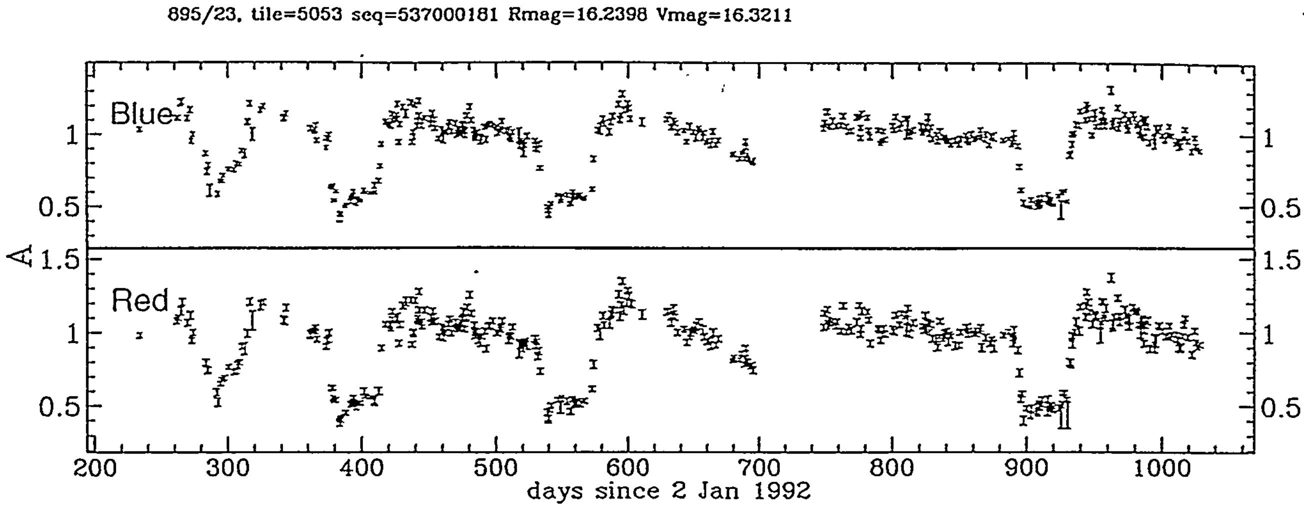

Fig. 7. Example of an unusual light curve; possible eclipsing binary.

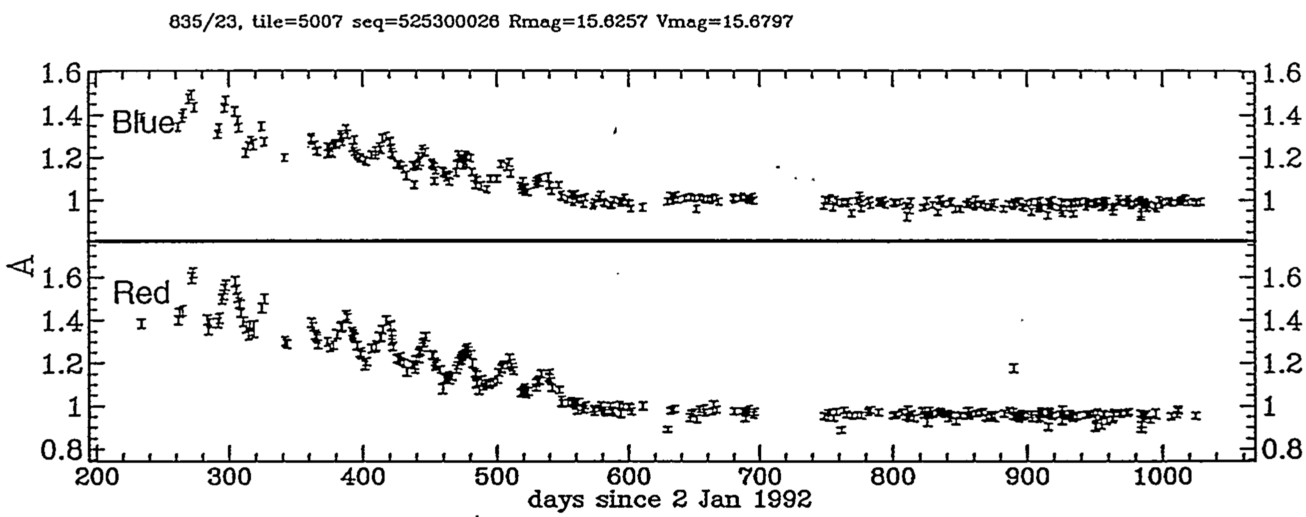

Fig. 8. Example of an unusual light curve.

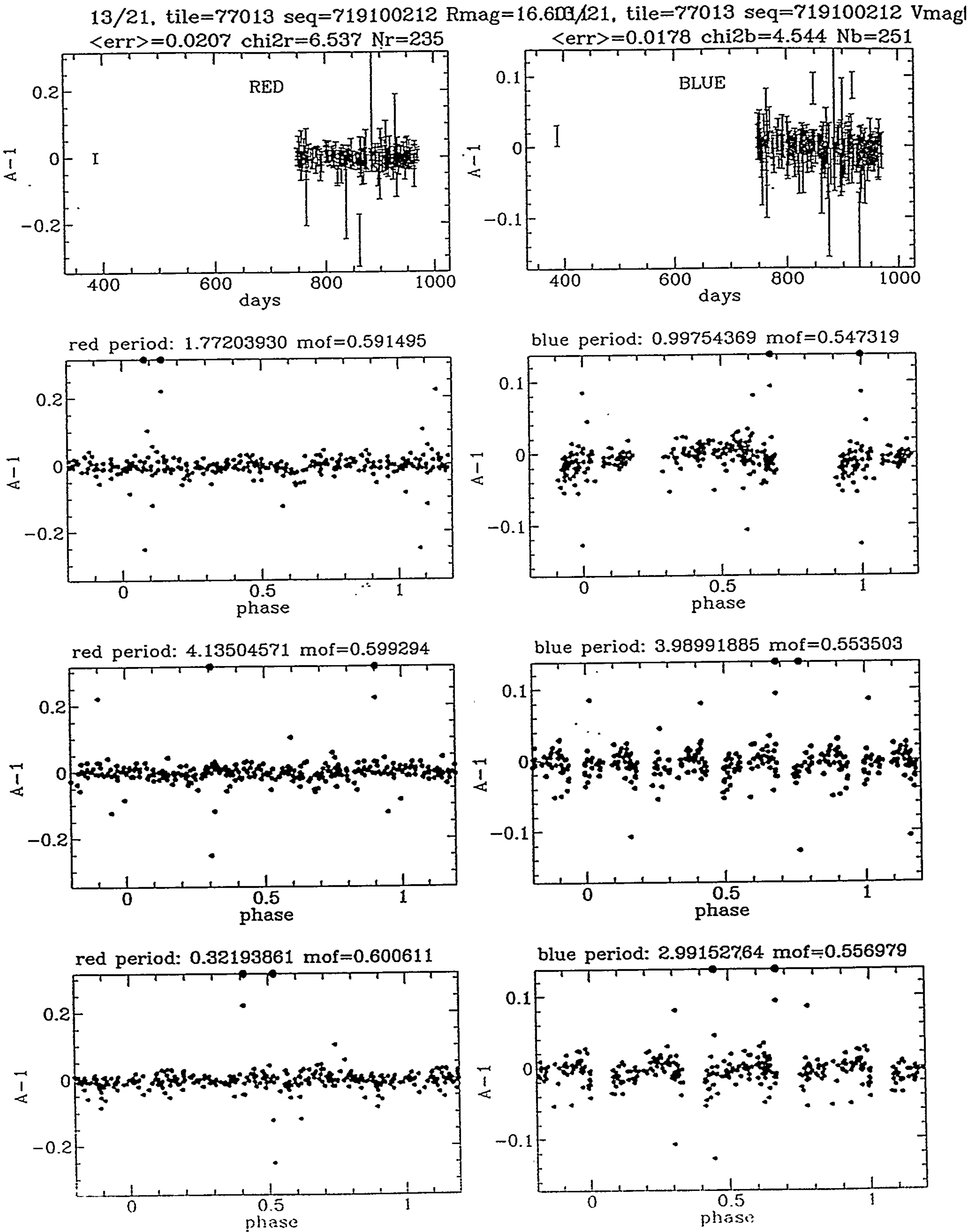

Fig. 9. Typical result of the phasing program. Red and blue light curves are shown in the top panels, phased with the top three periods in the following panels.

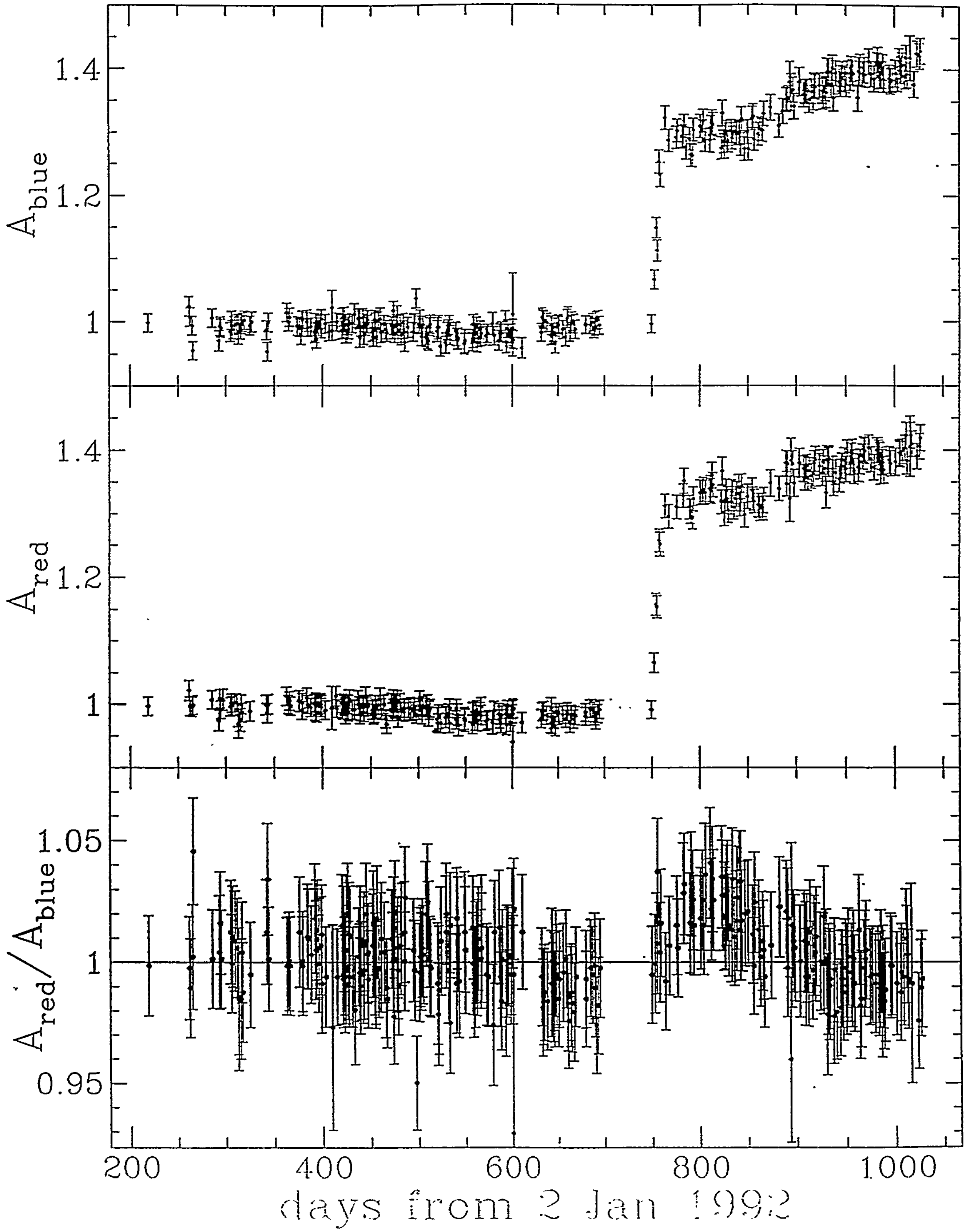

Fig. 10. Color curve of a stepper. The blue and red light curves are the top two panels. The bottom panel is the ratio of red to blue magnitude.

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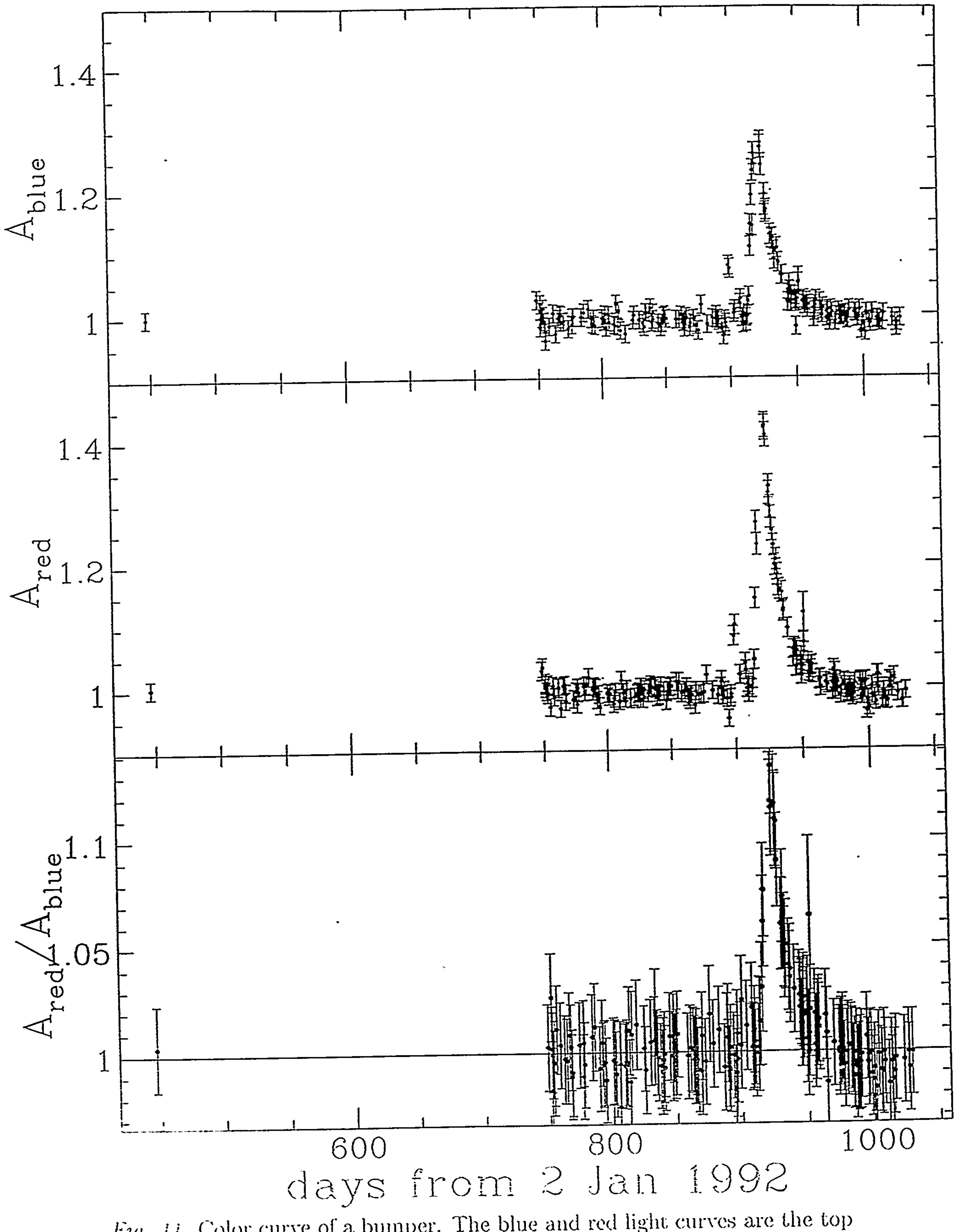

Fig. 11. Color curve of a bumper. The blue and red light curves are the top two panels. The bottom panel is the ratio of red to blue magnitude.

during the outburst. However, it is also possible that increased H-α emissions would cause the R_{MACHO} magnitudes to appear larger.

Some of the steppers display a different form of unusual color behavior; their color does not appear change when the brightness varies. In other words, they seem to be remaining at the same surface temperature, even though the stars are becoming brighter.

At this point in the search for low-level periodic variability, we have been unable to find evidence of such behavior in the quiescent stages of bumpers' light curves. This is unexpected, since most current theories on the causes of variability in this type of star predict low-level variations. For example, Sterken (1989) states that such low-level variations are present in normal supergiants and have been found in all luminous blue variables that have sufficiently accurate observations. In addition, the two competing theories on the causes of variations in Be stars predict periodicity of some type. Rotational modulation predicts single periodicity, and non-radial pulsation predicts multiperiodicity (see, for example, Baade & Balona 1994). Thus, it is unexpected that periodic variations have not been found in the stars in this catalog.

5 Conclusions

A catalog of approximately 400 aperiodic blue variables in the LMC was produced from the MACHO database. A preliminary classification of the catalog stars was attempted, based on the morphology of their light curves. Currently, the stars' positions are being correlated with known phenomena. Examination of the stars' color light curves shows that many steppers and bumpers display unusual color behavior. In a search for low-level periodic variability among bumpers with long quescient stages, there was an unexpected lack of conclusive evidence for such behavior. As a result, many of the stars in the catalog are in need of further study.

References

[1] Baade, D. 1987. "Be Stars as Nonradial Pulsators." in *Physics of Be Stars*. eds. Arne Slettebak and Theodore P. Snow (New York: Cam-

bridge University Press), 361-383.

[2] Baade, D., and Balona, L.A. 1994. "Periodic Variability of Be Stars: Nonradial Pulsation or Rotational Modulation?" in *Pulsation, Rotation, and Mass Loss in Early-Type Stars*, IAU Symp. 162, eds. L.A. Balona *et al.* (Boston: Kluwer Academic Publishers), 311-324.

[3] Balona, L.A. 1990. "Short-Period Variability in Be Stars," *Monthly Notices of the Royal Astronomical Society* 245, 92-100.

[4] Friedman, Jerome H. 1984. "A Variable Span Smoother," Laboratory for Computational Statistics Technical Report No. 5, SLAC PUB-3477.

[5] Moskalik, Pawel. 1995. "New Results on Pulsating OB Stars," *Astrophysical Applications of Stellar Pulsation*, ASP Conf. Series 83, eds. R.S. Stobie and P.A. Whitlock, 44-55.

[6] Percy, John R. 1987. "Observations of Rapid Variability in Be Stars," in *Physics of Be Stars*, eds. Arne Slettebak and Theodore P. Snow (New York: Cambridge University Press), 49-65.

[7] Sterken, C. 1989. "Photometric Variability of Luminous Blue Variables in Quiescent State," in *Physics of Luminous Blue Variables*, eds. Kris Davidson *et al.* (Boston: Kluwer Academic Publishers), 59-66.

[8] Waelkens, C. 1991. "Slowly Pulsating B Stars," *Astronomy & Astrophysics* 246, 453-468.

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