Identifying Previously Uncatalogued Red Variable Stars in the Northern Sky Variability Survey

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Received November 30, 2008; revised December 23, 2008, and April 27, 2009; accepted May 26, 2009

Abstract Candidate variable stars in the publicly available data of the Northern Sky Variability Survey (NSVS) were identified by data mining the 2MASS survey for entries that matched the following criteria: Dec. > –20.000, ($J-K$) > 1.2, and J-magnitude < 7.000. A total of 1,233 such stars were identified: 1 type M, 64 type M:, 26 type SR:, and 1,142 type L:, with amplitudes between 0.3 magnitude and 3.4 magnitudes. Only stars not listed in the International Variable Star Index (VSX) at the time of submission or not identified as variable in SIMBAD have been included.

1. Introduction

The Northern Sky Variability Survey (NSVS) was conducted from Los Alamos, New Mexico, and used four unfiltered telephoto lenses equipped with CCD cameras. The entire northern sky was covered with a one-year baseline and up to 500 measurements per object. Some parts of the southern sky, between declinations 0° and –38°, were also covered but with fewer data points. At galactic latitudes |b| < 20° the data quality was reduced due to blending of stars resulting from the 14-arcseconds pixel size.

The pulsating red variable stars forming the subject of this study include Miras (M), semiregular (SR), and slow irregular (L) variables. The Miras and at least some of the SR variables are known to be on the asymptotic giant branch. Both the M and SR category variable stars obey period-luminosity relationships and so can be used as indicators of distance and as targets for studies of galactic kinematics.

A more detailed description of NSVS and a discussion of the importance of the red variable stars forming the subject of this survey was written by Woźniak *et al.* 2004.

It is important to appreciate that the boundaries between these three classes of variable stars are somewhat subjective, particularly so between SR and L variables. In a lot of cases data would need to be collected for many years before a definitive classification could be made.

Mira variables have periods between 80 and 1,000 days and light amplitudes between 2.5 magnitudes and 11 magnitudes in the V band, although infrared amplitudes can be less than 2.5 magnitudes. In situations where the observed amplitude is greater than 1–1.5 magnitudes, but where it is not certain that the full amplitude is greater than 2.5 magnitudes, the symbol M: can be used.

SR variables differ from Miras in having a visual amplitude of less than 2.5 magnitudes and/or a less regular light curve that may be interrupted by irregularities. The period of SR stars varies from 20 to over 2,000 days and the amplitude varies from less than 0.1 magnitude to several magnitudes.

There are four subtypes of semiregular variable stars:

SRa—Late type giants showing persistent periodicity, though both the amplitude and shape of the light curve vary between cycles. SRa stars can be distinguished from Mira type variables by the smaller amplitude.

SRb—Late type giants with poorly defined periodicity that might include spells of little or no variation.

SRc—Late type supergiants with amplitudes of about 1 magnitude.

SRd—Giants and supergiants of spectral classes F, G, and K that sometimes show emission lines in their spectra and with amplitudes in the range of 0.1 to 4.0 magnitudes.

Slow irregular (L) variable stars show little or no evidence of periodicity. Unfortunately, many stars are placed in this category because they have not been studied for long enough to allow accurate analysis of the light curve.

2. Data

Identification and classification of these red variable stars required time-resolved photometry and examination of the resultant light curve.

The one year of NSVS data was examined using the SQL interface available from the Skydot website (http://skydot.lanl.gov/nsvs/nsvs.php). The default settings for the eight extraction and seven photometric correction flags within the NSVS user interface were used except—following the suggestion of Wils, Lloyd, and Bernhard (2006)—the APINCOMPL flag was set and the RADECFLIP flags were unset. The function of the various quality flags are summarized in Table 1.

Wide field images of the type used in this survey are prone to photometric problems such as color-dependent atmospheric extinction and color-independent (gray) extinction due to thin cloud. These issues were minimized using the technique of local photometric corrections.

For each of the 644 fields a template was prepared for all persistent objects including the median object magnitude and the standard deviation of individual magnitudes around the median. By comparing the template results with those obtained from each exposure, photometric problems could be identified and quantified and the necessary corrections applied. This was done individually to each of 100 macro pixels—each of which comprised 200 × 200 detector pixels—each time a field was imaged.

The observed magnitude scatter, as used to generate error bars on the light curves, was based on the work of Wils, Lloyd, and Bernhard (2006) and is presented as Table 2.

In November 2006, when candidate variables were being identified and examined via the NSVS interface, the results were available in two forms. A light curve was generated automatically and the photometry contributing to the light curve was available in tabular form. Unfortunately the plotting of the light curve has been "temporarily unavailable" since early 2008.

The operational characteristics of NSVS created some photometric difficulties. The resolution of the four CCD cameras corresponded to a pixel size of 14.4 arcseconds and this resulted in significant cross-contamination between objects, particularly in crowded fields. The wide spectral response of the unfiltered charge-coupled devices used means that the quoted magnitude figures are most comparable to Cousins *R*-band values.

3. Object selection

The NSVS database contained nearly twenty million light curves so it was important to use selection criteria that would specifically identify red variable stars. Candidates were identified by data mining the Two-Micron All Sky Survey (2MASS, Skrutskie *et al.* 2006) for entries that matched the following criteria: Declination > –20.000, $(J–K) > 1.2$, and J-magnitude < 7.000. Stars matching all of these criteria would, respectively, fall within the region of the sky covered by NSVS, would be red in color, and would be bright enough for reliable photometry.

Although the positional accuracy of the 2MASS survey far exceeded that of NSVS there was little difficulty in matching specific NSVS entries to the 2MASS red stars previously identified by their magnitude in two different 2MASS pass bands. This was despite the use of a fairly conservative search radius of 15 arcseconds. In a number of cases one 2MASS entry matched up to two or more NSVS entries and such instances are reported in the results spreadsheet.

The light curves for all candidates were examined by eye to check for clear evidence of variability. Inevitably there was some subjectivity in this decision and a number of factors were taken into account.

Figures 1 and 2 are examples of slightly noisier curves, both showing evidence of a maximum or minimum magnitude being reached. This was taken as strong evidence of genuine variability.

Figure 3 is an example of a light curve where the overall variation in magnitude far exceeded any noise in the data. This, too, was taken as strong evidence of genuine variability.

In some cases almost all the observed amplitude of variation was due to a small number of outlying values. In such cases the variability was regarded as unproven and no further data processing was carried out.

As a further check, the magnitude data for a group of fifteen stars, provisionally identified as variable during the survey, were averaged over a range of dates and the results plotted to see if there was any evidence for a residual trend. If the average magnitude of the fifteen stars showed a consistent pattern of brightening or fading over time, then it would be possible for a star to be identified as variable purely on the basis of this systematic error rather than due to any change in the behavior of the star itself. The gradient of the resulting graph (+0.0007) was not indicative of any residual trend likely to invalidate any previous assessments of variability.

For over half of all the candidate variables examined there was no reliable light curve available from the NSVS archive. This was usually in those parts of the sky where blending of the stellar images was a problem, that is where |b| < 20°. In a small percentage of cases, despite there being enough photometry, there was insufficient evidence of variability. This was usually confined to fainter candidate variable stars where the noise in the data was proportionately greater.

As a final check, only stars not listed in the *Combined General Catalogue of Variable Stars* (Samus *et al.* 2004), *New Catalogue of Suspected Variable Stars and Supplement* (Kazarovets *et al.* 1998), *Red Variables in the NSVS* (Woźniak *et al.* 2004), not identified as variable in SIMBAD, or not identified as variable in the International Variable Star Index (VSX, Watson *et al.* 2007) at the time of original submission to the VSX moderation process have been included in the 1,233 "new discoveries."

4. Periods and amplitudes

The *General Catalogue of Variable Stars* (GCVS) classification scheme for these red variable stars is based only on the amplitude and regularity of the visual variation. Kiss *et al.* (1999) explored the factors that contributed to making an accurate assessment of these two key variables. They concluded that a continuous time-series lasting "a few decades, at least" was required. Providing the time-series is long enough both the period and amplitude determinations were "almost completely independent of the S/N ratio."

The time span of the NSVS results at twelve months was insufficient in the vast majority of cases for a valid estimate to be made of the period of variation. Similarly for these long period variable stars, twelve months of NSVS data is most unlikely to demonstrate the full amplitude of variation in the pass band used by the survey. Red variable stars also have a smaller amplitude in this pass band, most comparable to Cousins *R* band, than in the *V* band used by GCVS in the basis for classification.

The implication of these caveats is that any assignment of variability type in this list should be viewed as highly provisional. Many, particularly longer period, SR: variable stars will have been classified as L: variables due to insufficient data for an estimate of the period, and Mira variable stars will tend to get classified as SR: variables through under-estimation of the amplitude.

Any variable star with an amplitude of greater than 1.5 magnitudes and showing no sign of irregularity within the year of observation was provisionally classified as M:.

Variable stars with amplitudes of less than 1.5 magnitudes or showing clear departures from single-maximum periodicity were provisionally classified as SR: or L:. The distinction between SR: or L:—being based on a visual examination of the light curve—was somewhat subjective, but all stars for which it was possible to calculate a period of variation were automatically classified as SR:.

5. Reliability and completeness

All these new entries that were accepted into the International Variable Star Index (VSX) (http://www.aavso.org/vsx/) were required to go through a moderation process.

In the case of this survey every entry was subject to a clerical and then to an astronomical check by a volunteer moderator. VSX moderators are experienced observers and have usually looked at thousands of light curves in the course of their studies. The clerical check was used to ensure that the associated data files were complete and free from error, that the star was "clearly variable" based on the NSVS data, and that at the time that VSX was checked—November 2006 to January 2007—that the variability of each new entry had not previously been reported. Of course, any remaining errors are the responsibility of the author and not the moderator.

The joint astronomical check was used to inform the decision on the most appropriate classification to allocate to a small number of the candidate variable stars. This usually involved replacing a classification of L: with SR:.

6. Data access and light curves

Figures 1 and 2 illustrate the light curves of two of the higher amplitude variable stars discovered during the course of this project. In both cases a provisional classification of M: seems justified, although the previously mentioned caveats should not be ignored.

Figure 3 illustrates an example of a variable star with a provisional classification of SR, and Figure 6 illustrates a star that, while clearly variable, is difficult to classify.

Figures 4, 5, and 7 illustrate the variety of long period variables covered in this paper. The number of data points, the period covered by the graph, and the observed amplitude of variation all vary significantly.

All data relating to the new discoveries discussed in this paper can be downloaded from http://www.martin-nicholson.info/nsvs.xls. This file will also be archived and made available through the AAVSO ftp site at ftp://ftp.aavso.org/public/datasets/jnichm372.xls. The spreadsheet contains positional information, numerical identifiers (including 2MASS, GSC, Tycho, and IRAS data where available), magnitude data in six pass bands, spectral type, links to the original NSVS data, provisional variability type, period, epoch, and an estimate of the maximum and minimum magnitude of the variable star.

The spectral types quoted in the spreadsheet were obtained by cross referencing the 2MASS positions with the *Catalogue of Stellar Spectral Classifications* (Skiff 2008). These can be accessed via: http://vizier.u-strasbg.fr/viz-bin/VizieR?-source=B/mk.

7. Summary

A search for previously uncatalogued red variable stars in the publicly available data of the Northern Sky Variability Survey (NSVS) yielded a total of 1,233 such stars. These were all passed through the International Variable Star Index moderation process prior to inclusion in the database.

Only stars not listed in the *Combined General Catalogue of Variable Stars* (Samus *et al.* 2004), or in the *New Catalogue of Suspected Variable Stars and Supplement* (Kazarovets *et al.* 1998), or in *Red Variables in the NSVS* (Woźniak *et al.* 2004), or in VSX at the time of submission, or not identified as variable in SIMBAD have been included.

8. Acknowledgements

This publication makes use of data products from the Two Micron All Sky Survey, which is a joint project of the University of Massachusetts and the Infrared Processing and Analysis Center/California Institute of Technology, funded by the National Aeronautics and Space Administration and the National Science Foundation.

This research has made use of the SIMBAD database, operated at Centre de Données astronomiques de Strasbourg (CDS), Strasbourg, France.

Patrick Wils acted as moderator for the VSX online database.

References

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Table 1. The NSVS data quality flags and their functions.

Data quality flag used	*Nature of problem*
SATURATED	Object has at least 1 saturated pixel
APINCOMPL	Aperture data incomplete or corrupted
NOCORR	Relative photometry correction could not be calculated
LONPTS	Low number of points in a macropixel
HISCAT	High scatter of magnitude differences in macropixel (> 0.2 mag.)
HICORR	High value of correction (> 0.1 mag.)
HISIGCORR	High scatter of corrections across the map (> 0.1 mag.)

Table 2. NSVS standard deviations as a function of magnitude.

NSVS Magnitude	*Average standard deviation*
9	0.04
10	0.03
11	0.03
12	0.04
13	0.07
14	0.12
15	0.2

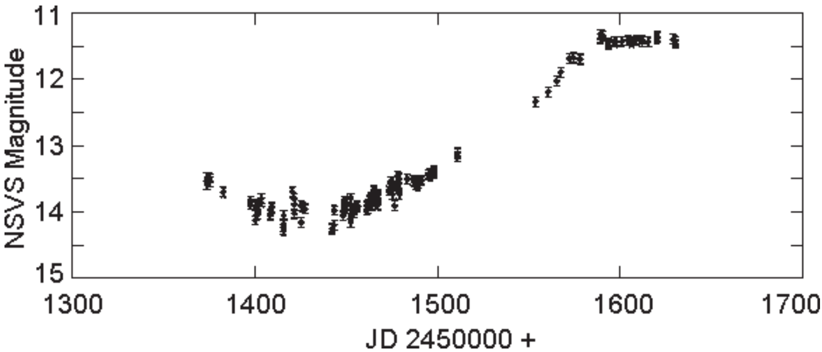

Figure 1. Star 2MASS 03415975+5542172 (#123), variable star type M:, in Camelopardalis.

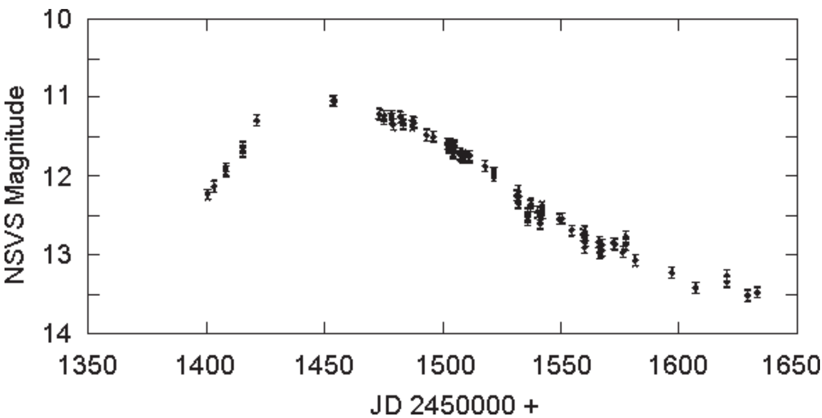

Figure 2. Star 2MASS 05045383+4657167 (#159), variable star type M:, in Auriga.

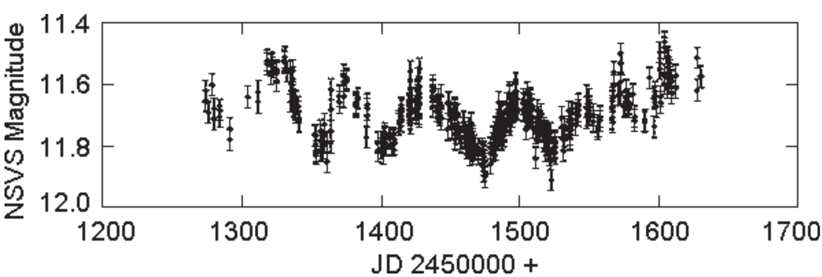

Figure 3. Star 2MASS 23325563+6746211 (#1214), variable star type SR:, in Cepheus.

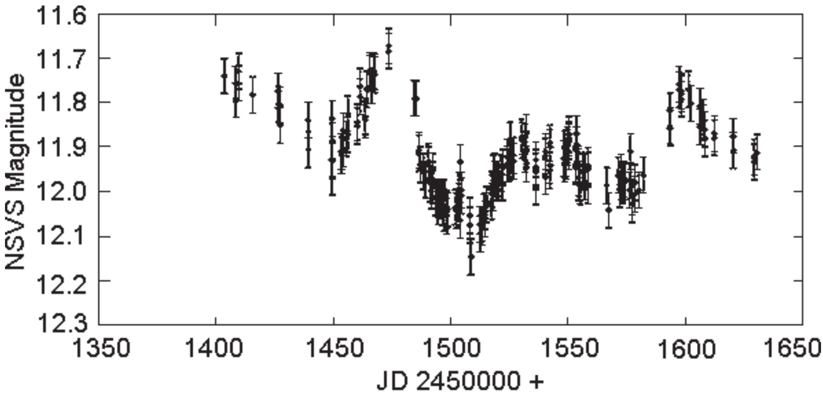

Figure 4. Star 2MASS 05211246+1930271 (#167), variable star type L:, in Taurus.

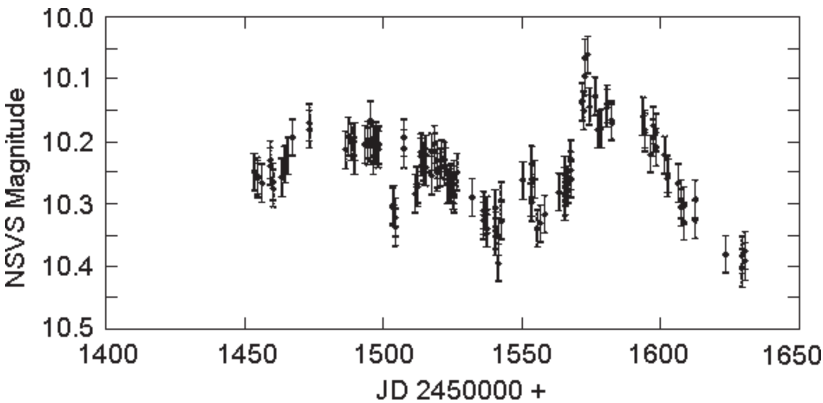

Figure 5. Star 2MASS 05443664+0236418 (#189), variable star type L:, in Orion.

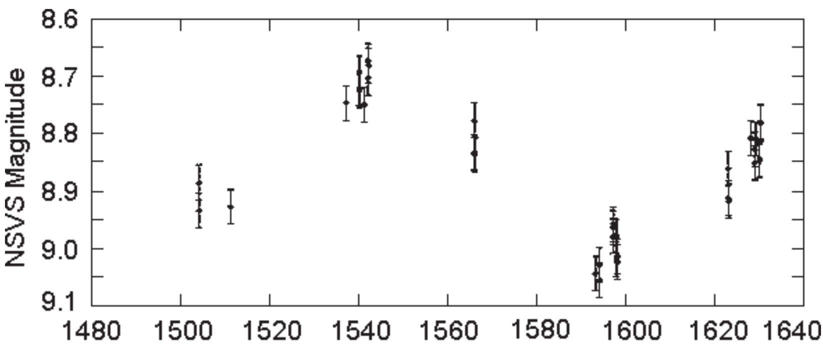

Figure 6. Star 2MASS 07065958+3136173 (#252), variable star type SR:, in Gemini.

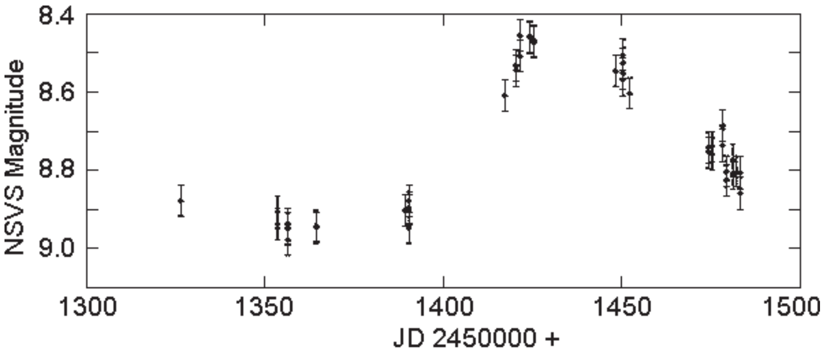

Figure 7. Star 2MASS 17200219-1556114 (#287), variable star type L:, in Serpens.

Figures—User notes:

1) The magnitude figures are most comparable to Cousins R *band values.*

2) The quoted variable star types are based on the classification system used within the General Catalogue of Variable Stars. This can be accessed at: http://www.sai.msu.su/groups/cluster/gcvs/gcvs/iii/vartype.txt

3) The quoted number—for example, #123—corresponds to the entry in the spreadsheet containing the data on each variable star.

4) Figures 1 through 7 include error bars based on the median magnitude of the variable star and the data listed in Table 2.