MONITORING OF SPECTRAL VARIATIONS OF MIRA-TYPE AND SEMIREGULAR VARIABLE STARS

G.M. Rudnitskij

Sternberg Astronomical Institute, Moscow State University
13 Universitetskij prospekt, Moscow, 119992 Russia, *gmr@sai.msu.ru*

ABSTRACT. The results of monitoring of a sample of late-type variable stars (Mira Ceti-type and semiregulars) are reported. Since 1980 a sample of 60 stars has been observed in the maser line of the H_2O molecule at a wavelength of 1.35 cm. These observations are performed on the RT-22 radio telescope of the Pushchino Radio Astronomy Observatory (Moscow Region). Since 1994 optical spectra of some of these stars have also been monitored on the 1.25-meter telescope of the Crimean Laboratory of the Sternberg Astronomical Institute. Regularities in the spectral behavior of the stars are discussed. Variations of the circumstellar H_2O masers correlate with the visual light curves (AFOEV and AAVSO data) with a time lag of 0.3–0.4P (P is the star's period). Flares of the Hα emission noted in R Leo, U Aur, R Cas, and R LMi were followed 1.5–2 years later by corresponding flares of the H_2O masers. These phenomena are interpreted as a consequence of propagation of a shock wave driven by stellar pulsation. Alternatively, the shock can be produced by motion of a low-mass satellite (a planet or a brown dwarf) in the inner layer of the circumstellar envelope. The effects of such a satellite on the spectrum and light curve of the primary star are discussed.

Key words: Stars: AGB and post-AGB; variables: others; masers; radio lines: stars; stars: individual: U Aur, S CrB.

1. Introduction

Long-period variable (LPV) stars are of great interest, since they represent the final stage in the evolution of solar-type stars. They represent one of the most numerous group among variable stars (several thousands, according to the latest surveys, e.g., NSVS[1]). Their periods (or light cycles) P range from $\sim 100^{\rm d}$ to $\sim 600^{\rm d}$. At the LPV stage the stars actively lose mass at a rate of $\sim 10^{-7}$–$10^{-5} {\rm M}_\odot$/year. The lost material forms extended circumstellar gas–dust envelopes hosting molecular maser radio sources. Several hundred LPVs are known to be sources of maser radio emission in molecular lines (OH, H_2O, SiO). This emission is highly time-variable, especially in the 6_{16}–5_{23} H_2O rotational line at $\lambda = 1.35$ cm. To understand the nature of the H_2O maser variability, our team has begun monitoring of a sample of LPVs in the H_2O line and optical spectrum. Periodic appearance of optical emission lines may suggest the presence of shock waves, which determine the LPV photometric and spectral variations. To connect the LPV variations in the optical and microwave ranges, we have undertaken long-term multiwavelength monitoring of sample of stars that includes several tens of Mira-type and semiregular variables. Here I report some results of this monitoring together with a model explaining particulars of LPV behavior.

2. Observations

Radio observations in the H_2O line at $\lambda = 1.35$ cm have been performed since 1980 on the 22-meter radio telescope at Pushchino Radio Astronomy Observatory (Astro Space Center of the Lebedev Institute of Physics, Russian Academy of Sciences) jointly with PRAO colleagues. We use a 1.35-cm wavelength receiver with a helium-cooled FET amplifier and a 128-channel filter-bank spectrometer with a resolution of 0.1 km/s. Since December 2005 we also use for spectral analysis of the signal a 2048-channel autocorrelator with a total bandwidth of 12.5 km/s and velocity resolution of 0.082 km/s. Intervals between consecutive observing sessions normally do not exceed 1–2 months.

Since 1994, our team has been monitoring a sample of about 30 Miras in the Hα line, see Esipov et al. (1999) and references therein. For optical spectroscopy, we use a diffraction spectrograph with a maximum resolution of 0.25 Å/pixel. An echellé spectrograph with a resolving power of 10,000 has been tested. The spectra are recorded with ST-6 and ST-8 Santa Barbara Instruments Group[2] CCD cameras (Table 1). This instrumentation is in operation on the 125-cm telescope

[1] http://skydot.lanl.gov/nsvs/red_variables.php

[2] http://www.sbig.com/

at the Crimean Laboratory of the Sternberg Astronomical Institute.

Table 1: CCD cameras utilized in the observations

Camera	$\lambda\lambda$, Å	$\Delta\lambda$, Å
ST-6I	4000–11,000	
600 lines per mm	5700–7700	5 or 2.5
1200 lines per mm	6000–7000	2.5 or 1.25
ST-6V	4000–11,000	–”–
ST-8		
1200 lines per mm	6300–6700	0.25

In the radio continuum, we have observed a sample of 34 Miras and semiregular variables at $\lambda = 6$ and 3 cm on the Australia Telescope Compact Array in Narrabri (Chapman & Rudnitskij 1998). Our sample included mostly southern Miras and semiregulars as well as some well-known objects in common with our H_2O/Hα sample (o Cet, U Ori, W Hya, R Aql). However, the result was negative: only upper limits on the flux density were determined, from 0.1 to 0.4 mJy.

3. Results

Figures 1, 2 illustrate the behaviour of U Aur and S CrB in the visual light, Hα, and H_2O lines. The effect we observe is typical for many stars of the sample. The curve of the integrated H_2O line flux follows the visual light curve with some phase delay $\Delta\varphi \sim 0.3$–$0.4P$, where P is the stellar period. However, maximum visual–H_2O correlation may have place not promptly, within the same light cycle, but several periods later, as we have found in RS Vir (Lekht et al. 2001).

We have traced the evolution of the Hα emission in about 30 stars (R Aql, R Leo, R Cas, U Her, χ Cyg, and others, Table 2). The appearance of the emission is not regular, not all light cycles are accompanied by it. The emission flared at different light phases φ of the stars, from minimum to maximum, although phases $\varphi \sim 0.4$–0.5 seem to be preferred. Some stars showed rather erratic behaviour of the Hα emission. Some others, during our monitoring interval, displayed isolated bursts of the Hα emission, followed (about a year and a half later) by a flare of the H_2O maser radio emission. These stars are R Leo (see Esipov et al. 1999 for details), R Cas, and U Aur. We have been tracing their H_2O maser history since early 1980s (Berulis et al. 1983), when they were rather strong H_2O emitters, but soon faded and remained silent in the H_2O line until 1997–1998. Then the probably shock-stimulated flares happened, see model by Rudnitskij & Chuprikov (1990). Interpreting this in the framework of our model (see Section 4), this may be a periastron episode of a planet in a highly eccentric orbit with a period $P \sim 15$ years.

Table 2: Long-period variables monitored in 1994–2005 in the H_2O and Hα emission lines

Name	Type	P, d	H_2O	Notes
R Aql	M	284	+	H_2O^a
RR Aql	M	395	+	H_2O^b
U Aur	M	408	+	
RX Boo	SRb	340	+	H_2O^a
R Cnc	M	362	–	
R Cas	M	430	+	H_2O^c
T Cas	M	445	–	
Y Cas	M	413	+	H_2O^l
o Cet	M	332	–	
S CrB	M	360	+	
V CrB	M	358	–	C star
R Crt	SRb	160	+	H_2O^a
S Crt	SRb	155	+	H_2O^a
W Cyg	SRb	131	–	
χ Cyg	M	408	–	S star
RY Dra	SRb	331	–	C star
T Dra	M	422	–	C star
RU Her	M	485	–	
T Her	M	165	–	
U Her	M	406	+	$H_2O^{a,d}$
W Hya	SRa	361	+	$H_2O^{a,e}$
R Leo	M	310	+	$H_2O^{f,g}$
R LMi	M	372	+	
RW LMi	SRa	640	–	C star
U Ori	M	368	+	$H_2O^{a,h}$
R Peg	M	378	+	
S Per	SRc	822	+	H_2O^m
VX Sgr	SRc	732	+	H_2O^n
R Tri	M	267	+	
RS Vir	M	354	+	H_2O^i
RT Vir	SRb	155	+	$H_2O^{a,k}$
R UMa	M	302	–	

References to our observations in the H_2O line:
[a]Berulis et al. (1983); [b]Berulis et al. (1998);
[c]Pashchenko & Rudnitskij (2004);
[d]Kudashkina & Rudnitskij (1988);
[e]Rudnitskij et al. (1999); [f]Rudnitskij (1987);
[g]Esipov et al. (1999); [h]Rudnitskij et al. (2000);
[i]Lekht et al. (2001); [k]Lekht et al. (1999);
[l]Rudnitskij & Pashchenko (2005);
[m]Lekht et al. (2005);
[n]Rudnitskij & Pashchenko (1999).

As for the radio continuum survey, we hoped to find, in addition to the visual–H_2O and Hα–H_2O correlations, a radio continuum–H_2O correlation: the increases in the H_2O maser flux were supposed to be due to amplification of the varying underlying stellar continuum. The Hα–radio continuum correlation could also be of interest. The result was negative. The only star we could detect in the centimeter-wave radio continuum was the symbiotic Mira R Aqr, which is a well-known radio source (Dougherty et al. 1995 and references therein). The system R Aqr consists of a Mira variable with $P = 387^d$ and presumably a white dwarf in an eccentric orbit with $P_{orb} = 44$ years. Our result (integrated flux $S(6\ \mathrm{cm})$ = 17.2 mJy,

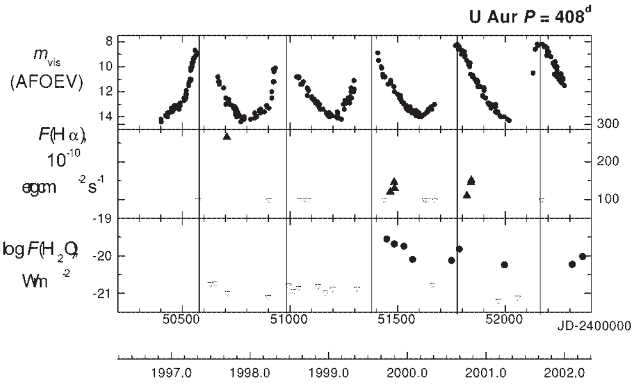

Figure 1: The data for the Mira variable U Aur: (a) visual light curve (AFOEV), (b) absolute flux in the Hα emission line, (c) integrated flux in the H_2O radio line.

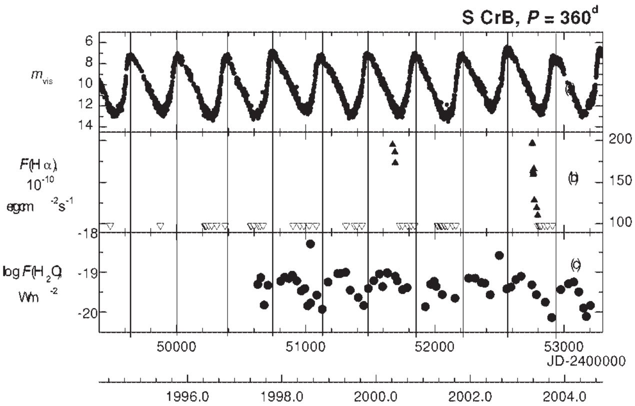

Figure 2: Same as in Fig. 1, but for the Mira variable S CrB.

$S(3\text{ cm}) = 15.9$ mJy) is quite consistent with the MERLIN result of Dougherty et al. (1995), 16 mJy at $\lambda = 6$ cm. This emission is produced by the common nebular envelope of the system R Aqr, its flat spectrum is consistent with that of an optically thin plasma cloud and is not related to the photosphere of the Mira component. The main conclusion of this experiment is that radio continuum from Miras is much weaker than expected for a postshock layer of ionized gas at shock velocity 15–20 km/s (required to produce strong Hα emission). One possible explanation is the presence of a slightly ionized "radio photosphere" (Reid & Menten 1997) that absorbs the radio continuum but lets out the optical emission freely.

4. The model for the observed variations

It is usually assumed that light variations of Mira-type stars are due to stellar pulsations. The pulsations produce strong shocks that ionize the stellar atmospheric gas thus exciting optical emission lines. However, our observations as well as those of other authors (e.g., Knapp et al. 1995, Reid & Menten 1997) have not detected strong radio continuum that would necessarily accompany the optical emission. One explanation is the "radio photosphere" of Reid & Menten (1997).

I propose an alternative hypothesis, which was initially published in the reports of Rudnitskij (2000, 2002). A similar idea was put forward independently by Berlioz-Arthaud (2003). Details can be found also on the Russian-language Astronet Web page (Rudnitskij 2005). The hypothesis explains the behavior of the optical emission lines across a Mira cycle and, probably, the photometric variability.

It is supposed that the optical line emission originates in a local source at the surface of the Mira atmosphere. This source can be a fireball around a nearby companion—a planet or a brown dwarf revolving in an orbit just outside the atmosphere, at a distance of about 1 AU from the stellar center. Its orbital velocity (~ 30 km/s for the central mass $\sim 1\mathrm{M}_\odot$) is highly supersonic. Estimates show (Rudnitskij 2002) that the conical shock around and behind the companion emits enough Hα quanta to account for the observed line fluxes shown in Figures 1 and 2. Moreover, the total brightness variations of a Mira can explained to a considerable extent by the "fireball" effect. Figure 3 shows the location of the companion's orbit with respect to the star and to the sky plane. Figure 4 presents model light curves due to the fireball radiation. At the right the projection of the orbit onto the sky plane is shown together with the assumed star and orbit parameters (asterisks mark the periastron). The amplitude of the model light curve in the V band can reach 2^m, which may be adequate for "regular" semiregulars (such as the quasi-periodic SRc star W Hya), but is somewhat low for Miras with visual amplitudes $\Delta m > 2.5^m$. However, this simplified model so far does not take into account secondary effects such as hard radiation of the shock, which reduces opacity around the fireball, thus uncovers deeper atmospheric layers and adds to the brightness variation. Another effect can be tidal excitation of nonradial pulsations by the motion of the companion in the atmosphere. These effects are to be considered in forthcoming publications. Finally, the trailing shock from the fireball reaches the masering region in the circumstellar envelope and causes an increase in the H_2O maser line flux.

The model describes well by purely geometrical effects any shape of the star's light curve. This is achieved by fitting several parameters (stellar mass M_*, stellar radius R_*, orbit inclination to the sky plane i, periastron longitude ω, semimajor axis a, eccentricity e). Especially interesting light curves are obtained in the case of eccentric orbits—asymmetry, bumps on the ascending/descending branches, and even double maxima (see Fig. 3), as observed, e.g., in the classical Miras R Cen and R Nor.

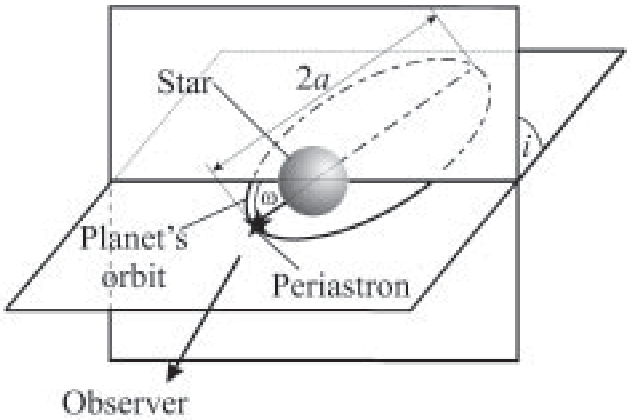

Figure 3: Parameters of the planetary orbit: $2a$ is the major axis, ω is the periastron longitude, i is the angle of inclination to the sky plane.

Irregularities in the brightness variation, which are rather typical in Miras (retarded or advanced maxima as compared to the mean light elements, different heights of the maxima), can be due to a superposition of a chaotic light-curve component. The Miras' light curves are known to consist of two addenda, regular and chaotic (Whitney 1984, Klyus 1988, Cannizzo et al. 1990). The latter component arises from intrinsic (rather erratic) stellar pulsation, whereas the regular component is imposed by the companion's orbital motion. In this hypothesis semiregular variables possess only this chaos; they have no companion in a suitable orbit to maintain the regular Mira-type variation.

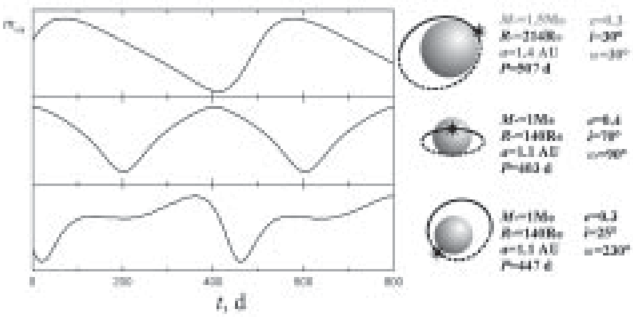

Figure 4: Model light curves for different parameters of the companion's orbit (see text).

Interestingly, the model explains also the period–luminosity dependence for Miras. Many versions of this relationship can be found in the literature, beginning from the classical paper of Clayton & Feast (1969), who gave this dependence in a tabular form (P *versus* M_V) for Miras in the Large Magellanic Cloud. Newer works usually give this dependence as $M = -m \log P + n$ (where m and n are some constants) and use infrared stellar magnitudes. The advantages of this approach are that (a) amplitudes of Miras' light variations and maximum heights vary from cycle to cycle in the infrared much less than in the visual, (b) in the infrared the effect of interstellar extinction (which is usually difficult to take into account for such distant objects as Miras) is much less. Recently Knapp et al. (2003) derived the period – K-band absolute magnitude relationship as

$$M_K \propto -3.39(\pm 0.47) \log P. \quad (1)$$

The period–luminosity dependence in Miras is usually attributed to their pulsation properties. The "planetary" model of the Mira-type variability discussed in this paper, too, yields the correct value for the slope of the period–luminosity relation. Indeed, the star's luminosity $L \propto R_*^2$ and its absolute magnitude $M \propto -5 \log R_*$. On the other hand, if we accept that the star's period P is the period of revolution of a planet at the outskirts of the stellar atmosphere, then, according to Kepler's third law, $P \propto R_*^{3/2}$, and

$$M \propto -3.33 \log P, \quad (2)$$

in accordance with, e.g., relationship (1). The bolometric correction, mass, and effective temperature of the star affect this relationship rather weakly.

Moreover, the "planetary" hypothesis predicts a verisimilar value of the "pulsation constant", though in this case no actual pulsation is involved. The period P of revolution of a planet at distance R_* from the stellar center (at the outer boundary of its photosphere) depends on the stellar mass M_* as

$$P = 2\pi \sqrt{\frac{R_*^3}{GM_*}}. \quad (3)$$

The quantity in the radicand is inversely proportional to the mean density of the star ρ_*. This precisely matches the formula for the pulsation constant:

$$Q = P(M_*/\mathrm{M}_\odot)^{1/2}(R_*/\mathrm{R}_\odot)^{-3/2}, \quad (4)$$

For $M = 1\mathrm{M}_\odot$ and $R_* = 1$ AU we find $Q = 0.116$ d, which corresponds to the main-tone pulsation. This was shown by Berlioz-Arthaud (2003).

5. Conclusions

Our long-term monitoring of a sample of Miras has confirmed the correlation between the stars' visual brightness and integrated H_2O maser flux. The model for H_2O maser variability in late-type giants assume a direct impact of a moderate-velocity ($v_{sh} \sim 5$–10 km/s) shock, reaching the masering region in the circumstellar envelope (Rudnitskij & Chuprikov 1990). The delay between the optical and H_2O maxima depends on the shock travel time and may be as long as a few stellar periods (Lekht et al. 2001). The shock model is supported by Hα-line monitoring: appearance of strong

Balmer emission is a diagnostic for the early stage of shock propagation in the stellar atmosphere; as the weakened shock reaches the H_2O masering region at a few stellar radii outside, it results in an appropriate maser increase.

However, the model of a spherical shock, driven by the stellar pulsation and embracing the entire stellar surface, may be not valid. In this case the Balmer emission should be accompanied by emission in the radio continuum of the entire stellar disk that should be observable at centimeter waves. We could not detect in the radio continuum even the stars previously known to be radio continuum sources (*o* Cet, R Aql, W Hya, Knapp et al. 1995, Reid & Menten 1997), though the sensitivity was sufficient (typically 0.1–0.3 mJy at the 3σ level). The upper levels obtained imply that strong spherical shocks with front velocities $v_{\rm sh} \geq 15$–20 km/s do not exist in Miras or they may be invisible at microwaves, because they do not propagate above the radius of the "radio photosphere", $r_{\rm ph} \sim 2R_*$ (Reid & Menten 1997), strongly absorbing the radio emission, but transmitting the optical emission.

An alternative to the pulsation-driven shock is proposed. The Balmer emission comes from a local source—fireball surrounding a nearby companion (brown dwarf or planet) revolving around the expanded red giant. The fireball is undetectable at microwaves because of its small angular size. The model accounts well for the appearance of the optical emission lines, it also reproduces the variations of the H_2O maser, the shape of the visual light curves, and the period–luminosity dependence for Miras.

Acknowledgements. The author is grateful to V.F. Esipov for the optical spectroscopy data, to M.I. Pashchenko, E.E. Lekht, S.V. Rottar, V.A. Samodurov, I.A. Subaev, and A.V. Tolmachev for help with the H_2O observations, to Jessica M. Chapman for joint *ATCA* observations. This work was supported by the Ministry of Industry and Science of the Russian Federation on the RT-22 radio telescope (facility registration number 01-10) and by the Russian Foundation for Basic Research (project code 06-02-16806). This research made use of the visual observations of the Association française des observateurs d'étoiles variables (AFOEV) from the SIMBAD database of the Centre des données astronomiques de Strasbourg (France).

References

Berlioz-Arthaud P.: 2003, *Astron. Astrophys.*, **397**, 943.

Berulis I.I., Lekht E.E., Pashchenko M.I., Rudnitskij G.M.: 1983, *Astron. Zh.*, **60**, 310.

Berulis I.I., Lekht E.E., Munitsyn V.A., Rudnitskij G.M.: 1998, *Astron. Zh.*, **75**, 394.

Cannizzo J.K., Goodings D.A., Mattei J.A. 1990: *Astrophys. J.*, **357**, 235.

Chapman J.M., Rudnitskij G.M. 1998: *Asymptotic Giant Branch Stars, IAU Symp. 191 Poster Session*, #P4-01.

Clayton M.L. & Feast, M.W. 1969, *MNRAS*, **146**, 411.

Dougherty S.M., Bode M.F, Lloyd H.M. *et al.* 1995, *MNRAS*, **272**, 843.

Esipov V.F., Pashchenko M.I., Rudnitskij G.M., Fomin S.V.: 1999, *Pis'ma Astron. Zh.*, **25**, 775.

Klyus I.A. 1988: *Peremennye Zvezdy*, **22**, 697.

Knapp G.R., Bowers P.F., Young K., Phillips T.G.: 1995, *Astrophys. J.*, **455**, 293.

Knapp G.R., Pourbaix D., Platais I., Jorissen A.: 2003, *Astron. Astrophys.*, **403**, 993.

Kudashkina L.S., Rudnitskij G.M.: 1988, *Peremennye Zvezdy*, **22**, 925.

Lekht E.E., Mendoza-Torres J.E., Pashchenko M.I., Berulis I.I.: 1999, *Astron. Astrophys.*, **343**, 241.

Lekht E.E., Mendoza-Torres J.E., Rudnitskij G.M., Tolmachev A.M.: 2001, *Astron. Astrophys.*, **376**, 928.

Lekht E.E., Rudnitskij G.M., Mendoza-Torres J.E., Tolmachev, A.M.: 2005, *Astron. Astrophys.*, **437**, 127.

Pashchenko M.I., Rudnitskij G.M.: 1999, *Astron. Zh.*, **76**, 363.

Pashchenko M.I., Rudnitskij G.M.: 2004, *Astron. Zh.*, **81**, 418.

Reid M.J., Menten K.M. 1997: *Astrophys. J.*, **476**, 327.

Rudnitskij G.M.: 1987, *Circumstellar Matter. Proc. 122 Symp. IAU*, Dordrecht: Reidel, 267.

Rudnitskij G.M.: 2000, *The Impact of Large-Scale Surveys on Pulsating Star Research. IAU Coll. 176, ASP Conf. Ser.*, **203**, 384.

Rudnitskij G.M.: 2002, *Publ. Astron. Soc. Australia*, **19**, 499.

Rudnitskij G.M.: 2005, *http://www.astronet.ru/db/msg/1202883.*

Rudnitskij G.M., Chuprikov A.A.: 1990, *Astron. Zh.*, **31**, 853.

Rudnitskij G.M., Pashchenko M.I.: 2005, *Pis'ma Astron. Zh.*, **31**, 853.

Rudnitskij G.M., Lekht E.E., Berulis I.I.: 1999, *Pis'ma Astron. Zh.*, **25**, 467.

Rudnitskij G.M., Lekht E.E., Mendoza-Torres J.E., *et al.*: 2000, *Astron. Astrophys. Suppl. Ser.*, **146**, 385.

Whitney C.A. 1984: *JAAVSO*, 13, 31.