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Mira Stars with Double Maxima: Humps, Bumps, and Resonances

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Abstract

We investigate the small class of long-period Mira variables that exhibit two distinct maxima during each pulsation cycle, and place them in the context of the general case of Miras with humps or bumps in their light curves. We present a sample of *AAVSO* and *ASAS* Miras with known or suspected double maxima. We show example light curves, describe their general characteristics, and consider competing models for explaining the phenomenon. If double maxima are due to resonances between pulsation modes, then they will be useful for studying the internal characteristics of Mira stars. If the cause is atmospheric filtering, where the pulsation period is longer than the acoustic cutoff period, then their utility will be for distinguishing among atmospheric models.

Introduction

Mira variables are stars at the tip of the asymptotic giant branch (AGB) with large amplitude pulsation (ΔV>2.5), periods greater than 100 days, and emission lines during at least part of the pulsation cycle. There is a broad range of behavior within this class, and stars may have regular or irregular light curves. Many Mira stars are known to have "bumps" on their light curves, and the phenomena may be attributable to multiple pulsation modes, atmospheric effects such as shocks, nonlinearity, or some combination of these.

A very small group of stars exhibit "double maxima", where the light curve reaches a local maximum twice during each pulsation cycle. The *General Catalogue of Variable Stars* lists five stars with such behavior: R Cen, R Nor, BH Cru, BN Sco, and UZ Cir, and a sixth, DH Cyg, should also be added to this list.

In this poster, we summarize the observational data for Miras with double maxima, and discuss common features found in these stars. We then put this into the context of the current theoretical understanding of Mira star pulsation, and consider possible physical causes of the phenomenon.

Name	Period (d)	Spectral Type
BH Cru	540	SC4.5/8-e-SC7/8-e ⇒CS?
BN Sco	620	M6
DH Cyg	527	M6
R Cen	505	M4e-M8IIe
R Nor	507	M3e-M6II
UZ Cir	538	M7e

Table 1: Periods and spectral types for the six Miras with known or suspected double maxima. All stars have periods above 500 days, and five of six are of spectral type M. Both BH Cru and R Cen have undergone significant period change, and R Cen is believed to be a thermally-pulsing star.

Observed Properties

All stars in this sample have periods over 500 days, suggesting they have some common physical characteristics. R Cen, R Nor, and DH Cyg consistently show unambiguous double maxima in their light curves (Figure 1), while BH Cru and UZ Cir (Figure 2) do not. BN Sco (also Figure 2) is not well-observed enough to determine its light curve shape.

Five of the six stars are classified as oxygen-rich, while BH Cru is a more carbon-rich Mira, so composition variations are unlikely to cause the double maxima. Long period Miras are on average more massive and have higher mass loss rates (Vassiliadis & Wood 1993; Willson 2000) but Whitelock, Marang, and Feast (2000) note that the IR colors of BH Cru, R Cen, and R Nor indicate lower mass loss rates, at or below 10^{-7} solar masses per year.

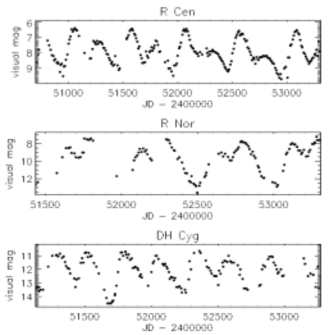

Figure 1: Recent AAVSO light curves for R Cen, R Nor, and DH Cyg. All three have well-defined double maxima. Light curves are 10-day averages of visual estimates from the AAVSO International Database (http://www.aavso.org).

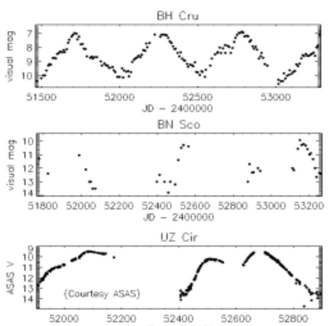

Figure 2: Recent light curves for BH Cru, BN Sco, and UZ Cir. Data for BH Cru and BN Sco are visual estimates from the AAVSO International Database; data for UZ Cir courtesy of ASAS (Pojmanski 2002). BH Cru and UZ Cir appear to have "moving bumps" rather than fixed double maxima, so their membership in this class is questionable. The available data for BN Sco are not yet sufficient to ascertain its behavior.

Causes of double maxima

There are at least two possible causes for the occurrence of double maxima in light curves, including:

- **simultaneous excitation of two pulsation modes with a period ratio of 2:1**
- **atmospheric filtering of pulsations with periods greater than the acoustic cutoff period**

The double-mode pulsation explanation is the preferred explanation for the 10-day break in Cepheid variables, and has recently been invoked by Lebzelter et al. (2004) to explain the double-peaked Miras R Cen and R Nor.

However, Bowen (1988, 1990) showed that when the pulsation period is greater than the minimum acoustic cutoff period in the atmosphere there are always *two* shocks per cycle; this could produce a hump or second maximum in the light curve. We use the term *atmospheric filtering* to refer to this phenomenon, as the pulsational signal that propagates outward develops a substantial component at the value of the acoustic cutoff period, P_{ac}, particularly as $P/P_{ac} \to 2$.

Here, we discuss both possibilities.

Double-mode pulsation

One view of this light curve behavior is that it is a manifestation of double-mode pulsation, where the higher radial order pulsation frequency is very close to twice that of the lower one, producing a double-peaked light curve. This is the most-commonly accepted reason for the existence of double-peaked light curves, both for Miras and for stars such as the bump Cepheids. Such a process in Miras would require that both modes are overstable and are excited to similar amplitudes. It would also result in other observable effects, such as a secondary maximum in radial velocity variations.

Double-mode pulsation: observables

Radial velocity variations

Radial velocity variations in double-mode Mira stars should show *two peaks*, as each mode generates radial motion of the photosphere. Lebzelter et al. (2004) measured the radial velocity variations of several AGB stars, including R Cen and R Nor. Interestingly, they found a dual-peaked RV curve for R Cen *but not for R Nor*. However, observations of R Nor did not cover the entire pulsation cycle, so this is not definite evidence against double-mode pulsations in this star.

Periods and period ratios

All six of our stars have periods at or above 500 days. If these are double-mode pulsators with a period ratio of 2, the modes almost certainly are fundamental and first overtone (Ostlie & Cox 1986; Wood et al. 1999). Both fundamental and first overtone modes are possible on theoretical grounds, a fact which led to a long debate about which modes were observed in Mira stars.

R Cen has been identified as going through a thermal pulse because of its large, long-term period decrease, and BH Cru also shows a large *dP/dt*. If both stars are indeed going through shell flashes, then *two of six stars* in our sample are in such a state. During a shell flash the radius varies substantially, making it possible that $P_0/P_1 = 2$ at some point, at least temporarily. In fact, the double maxima of both R Cen and BH Cru have become less pronounced in recent decades, consistent with the idea that these stars are moving away from the 2:1 period resonance.

Atmospheric filtering

Another possible explanation for the double maxima is the occurence of two shocks per cycle, which happens when the pulsation period exceeds the acoustic cutoff period, and becomes especially prominent when $P/P_{ac} \to 2$ (Bowen 1990). This is what we refer to as *atmospheric filtering*.

For $P < P_{ac}$, acoustic waves propagate freely from the interior through the atmosphere, and do not establish standing waves in the interior. This greatly increases the driving energy required to sustain large-amplitude pulsations. However, when $P > P_{ac}$, the waves do *not* propagate outward, but are reflected back into the interior. The standing wave thus produced requires far less driving energy to sustain large-amplitude pulsations, making it more likely such modes will be driven to observable amplitude. Bowen showed that a secondary shock of comparable power to the main shock is also produced when $P/P_{ac} \to 2$.

The acoustic cutoff period is proportional to the pressure scale height over the sound speed, which goes as TR^2/M. Because both T and R vary, the important region is where the *minimum* of this quantity occurs in the atmosphere. For P proportional to R^aM^{-b}, P/P_{ac} should scale as $R^{(a-2)}M^{(1-b)}$. If the Ostlie & Cox (1986) PMR relation (a=1.86, b=0.73) is assumed, the ratio is only a weak function of the stellar radius and mass. The direct dependence upon the mass suggests that more massive stars are more likely to approach this value, consistent with our sample stars being long-period Miras.

Atmospheric filtering: observables

Mass loss

Models suggest that pulsation together with dust formation are keys to mass loss from Miras (e.g. Bowen 1988, 1990). The dust is radiatively accelerated to escape velocity in a relatively short time, resulting in larger mass loss rates -- from 10^{-7} to 10^{-6} solar masses per year or more.

However, the mass loss rates from these stars are anomalously low (Whitelock, Marang, & Feast, 2000). This could be due to some inhibition of dust grain formation, *caused by* or *causing* the process leading to the double maxima.

Radial velocity variations

The observational effects of atmospheric filtering on the RV variations are less clear. The observed velocities would be dependent upon the optical depth of the line-forming regions, which could change during a strong atmospheric shock, and could also vary depending upon the line being used to make the measurement.

Although its RV curve did not cover a complete cycle, R Nor appeared to have a simple, single-peaked curve with no standstills. This would be consistent with the majority of the light being emitted by the surface undergoing single-mode pulsations. However, if the shock generated enough light to cause a secondary maximum in the light curve, the shocked region (and its radial velocity) should also appear in the spectrum. Therefore the consequences of this model on the observed radial velocity spectrum are not clear.

Discussion

Double-mode pulsation is commonly accepted as the reason for the existence of double maxima, but atmospheric filtering is also a possibility. Further observational work may help to distinguish between the two, including:

- **More extensive RV measurements for all stars**
- **Measuring the pulse phase of shock emission lines**
- **Better measurement of the mass loss rates**
- **Light curves in the IR**

Humps and bumps: the general case

We have discussed the very specific case of persistent double maxima. The more general case of bumps in Mira light curves is not understood. Some trends are evident: longer-period Miras more often show these variations than shorter-period ones. The spread in light curve asymmetry also increases with longer periods (Campbell 1955), though we note R Cen and R Nor have anomalously low asymmetries, which is consistent with their low mass loss rates (Bowers & Kerr 1977).

Non-linear pulsations and low-dimensional chaos have been investigated as possible mechanisms for variations in these and other stars (e.g. Cannizzo et al. 1990). The complex physical conditions in AGB stars may make this non-linear behavior more likely as well as more obvious. A better understanding of this phenomenon may be generally applicable to other pulsating AGB stars, as well as the RV Tauri variables which show similar behavior.

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