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PERSONALITIES OF MIRA VARIABLES AS REVEALED BY THEIR SPECTRA—VERDICT: BIZARRE!

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Abstract

The spectra of Mira variables are beautiful to the eye. They are also full of information about the temperature, pressure, chemical composition, and structure of the star. A general overview of some of the techniques for extracting this information will be given, with the strange behavior of the aluminum oxide molecule as a specific example.

1. Introduction

The spectra of the coolest stars are, in my opinion, the most beautiful of all to look at directly, using only the eye as detector. Not only do they have a gorgeous red color, but they also have a series of striking deep bands. In the 1860's, Father Angelo Secchi of the Vatican Observatory looked at the spectra of bright stars with a visual spectroscope. He saw them in all their glorious colors and, though the coolest stars are not very numerous, they were so striking in appearance that he was inspired to put the banded red stars in two of his four divisions. The Mira variables are a subset of these cool giants.

Other papers in this session will give more details of the spectra and their physical interpretation. I will give an overview based on the appearance of the blue-violet spectrum, which gives the clearest uncontaminated view of the photosphere. The red and infrared parts of the spectrum are heavily influenced by dust shells and by terrestrial absorptions (mainly oxygen and water vapor). There is very little ultraviolet light from the photospheres of these stars and most of the ultraviolet emission is from the chromosphere.

The red color is due to the cool temperature. The bands are due usually to titanium oxide (TiO) (M-type stars), though some of the Miras show only the Swan bands of carbon (C-type stars); more rarely, zirconium oxide (ZrO) is mixed in (S-type stars). The stars of these three types run in parallel temperature sequences and the differences in their spectra are due to small differences in abundances, not temperature as with the other spectral classes.

2. The coolest stars

The M-type, or TiO, stars are by far the most numerous. At M0, the TiO band on the red side of hydrogen-beta just begins to show at classification dispersion. With advancing type (decreasing temperature), the number and strength of bands increases, until at M8 or later the TiO bands extend almost to the ultraviolet (408.2 nm). In comparing with standard stars to determine the temperature type, one must be careful to use only band ratios, since there is frequently some "veiling," which decreases the absolute intensity of bands, but does not affect the ratios. Most of the lines, such as

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neutral calcium, increase steadily with temperature in normal stars with similar abundances. There are also, however, some weak-lined stars, so it is necessary to be careful, because the use of absolute line strengths (instead of ratios) can be very misleading.

The C stars are characterized by the presence of the Swan bands of the carbon molecule, C_2. These are quite strikingly different from the TiO bands, since the carbon bands decrease in strength blueward from the bandhead, whereas the TiO bands decrease redward from the bandhead. Also, there must be another absorber (triatomic carbon and silicon carbide have been suggested) because the carbon stars have the steepest energy distribution in the blue of any stars. They are extremely red stars, with B-V indices as red as 4, 5, or more. In the C stars, the C^{12}/C^{13} ratio is in the range of 10–20, whereas on earth it is more like 90. Carbon stars with enhanced C^{13} are referred to in the literature as J stars.

The pure S stars are characterized by the presence of ZrO bands, e.g. 461.9 nm (the nearest TiO band is at 462.6 nm). There are very few pure S stars; most are a mix with either M or C. It is interesting to note that while there are M-S stars, there are no M-C stars. There are a few S-C stars, but they are extremely rare; only about a dozen are known down to 15th magnitude. The reason that there are no M-C stars and very few S-C stars is that carbon and oxygen are almost totally used up in carbon monoxide. If $C > O$, then there is no oxygen available for TiO (or ZrO), so the result is a carbon star. If $C < O$, then there is no carbon available for CN or C_2, so the result is an "oxygen" star with molecules of TiO or ZrO. M and S stars have a C/O ratio of about 0.95 and C stars about 2, while S-C and M-S stars have a very narrow range of ($0.99 < C/O < 1.01$).

For more information on the coolest stars, see Keenan (1973) and the atlas of spectra by Keenan and McNeil (1976).

3. Long period variables (Miras)

The cooler the star, the more likely it is to be variable. Among the coolest stars (cooler than about 3,000 K), all are variable, more or less. This is partly because of various instabilities, but also partly because the peak of the Planck curve is way out in the IR, so visible light is on the tail of the energy distribution and large variations occur in the tail for small changes in the temperature. In the case of the Mira variables, the light variations in the visible region are greater than 2.5 magnitudes (by definition) and are frequently 5 magnitudes, with periods of a year, more or less (with a range of 3 months to a few years). However, the absorption lines are not much affected by being on the tail of the energy distribution, so line studies should be more reliable than broad-band, visual photometry. IR photometry is also very good, especially narrow-band photometry of bands.

The Mira variables are identifiable spectroscopically by the presence of high-excitation emission lines, such as H and Fe II, as well as a number of forbidden lines. These lines vary around the cycle, being strongest at and after maximum, weakest after minimum. (See Keenan *et al.* 1974, for the northern Miras and Crowe 1984, Crowe and Garrison 1988, for the southern Miras.) At first, it was thought that they were from a hot shell, but that model was soon abandoned in favor of a shock model. The current models involve two-shocks or multi-shocks (Willson 1997).

The spectra exhibit many bizarre kinds of phenomena, including "veiling," line-doubling, etc. (Merrill *et al.* 1962), which make them either a spectroscopist's dream or nightmare, depending on whether order or chaos is more appealing. I find the Mira variables fascinating, but they are a sink for telescope time, as well as for astronomers' time and energy. Each star is unique and variations from cycle to cycle for a given star are common. On the other hand, Miras have given us insight into stellar pulsation,

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stellar evolution, and the morphology and history of the Galaxy, as well as differences among galaxies. They are interesting!

4. Semiregular and irregular variables

Spectroscopically, semiregular and irregular variables are simply mild Mira variables, with many of the same characteristics, but less pronounced; e.g., the emission is weaker. Photometrically, their variations are less extreme (less than 2.5 magnitudes, by definition). Some of the above references include these stars.

5. Behavior of the aluminum oxide molecule

The aluminum oxide (AlO) molecule is a case in point. In normal M-type giant stars, it strengthens predictably with decreasing temperature. In Miras, it can be extremely strong or weak in absorption, or in emission, all in the same star at the same phase (i.e., more or less the same temperature) of difference cycles. AlO emission at the 484.2 nm bandhead was first discovered by Joy (1926) in Mira itself. Since then, it has been seen in a few other stars (e.g., R Cnc) and has been confirmed by identification at high dispersion of several bandheads, also clearly in emission. (See Garrison 1972, and Keenan *et al.* 1969 for illustrations and details.) Figure 1 is a CCD spectrum of Mira, taken in August 1996, showing the main AlO bandhead near hydrogen beta.

In an attempt to discover trends, many parameters were plotted against the AlO band strength (with emission corresponding to negative strength). The only star for which a very long baseline of data is available in the Mt. Wilson archives is Mira itself. Until the 1970's, spectra were taken at most maxima since 1916. Though the monitoring is not continuing at Mt. Wilson, my students and I have been taking spectra of Mira regularly with both the 1.88-m telescope at the David Dunlap Observatory and the 60-cm Helen Sawyer Hogg telescope of the University of Toronto Southern Observatory in Chile.

A plot of aluminum line strength against AlO band strength for Mira shows no trend. A plot of temperature at maximum shows no correlation. A slight, but not very convincing, trend is seen in a plot of height of maximum versus AlO band strength. However, a plot of veiling versus AlO strength shows a striking correlation, in the sense of strong-line cycles exhibiting strong AlO band strength, while weak-line cycles show weak or no AlO. AlO emission shows up only in the weakest-line cycles. The spectra are of mixed quality, so there is some scatter in the correlation, but the trend is clear and the error bars do not preclude a perfect correlation.

So what is going on here? Are there high-level clouds of AlO floating around the atmospheres of some Miras? As is often said: "more data are needed." Monitoring of the light curves and with medium-resolution spectra as well as high-resolution spectra of many Miras at maximum light over many cycles is very useful in deciding among alternative models.

6. Conclusion

Studies of Miras are difficult because of the long periods and the individuality of these wonderfully strange stars. AAVSO data on the light curves of Miras collected over the past 100 years has been and will continue to be invaluable in any investigation of the properties of these strange stars. Astronomers are indebted to the AAVSO observers and their tireless efforts as well as to AAVSO Headquarters for archiving, organizing, and distributing the data. Keep up the good work; we need your help!

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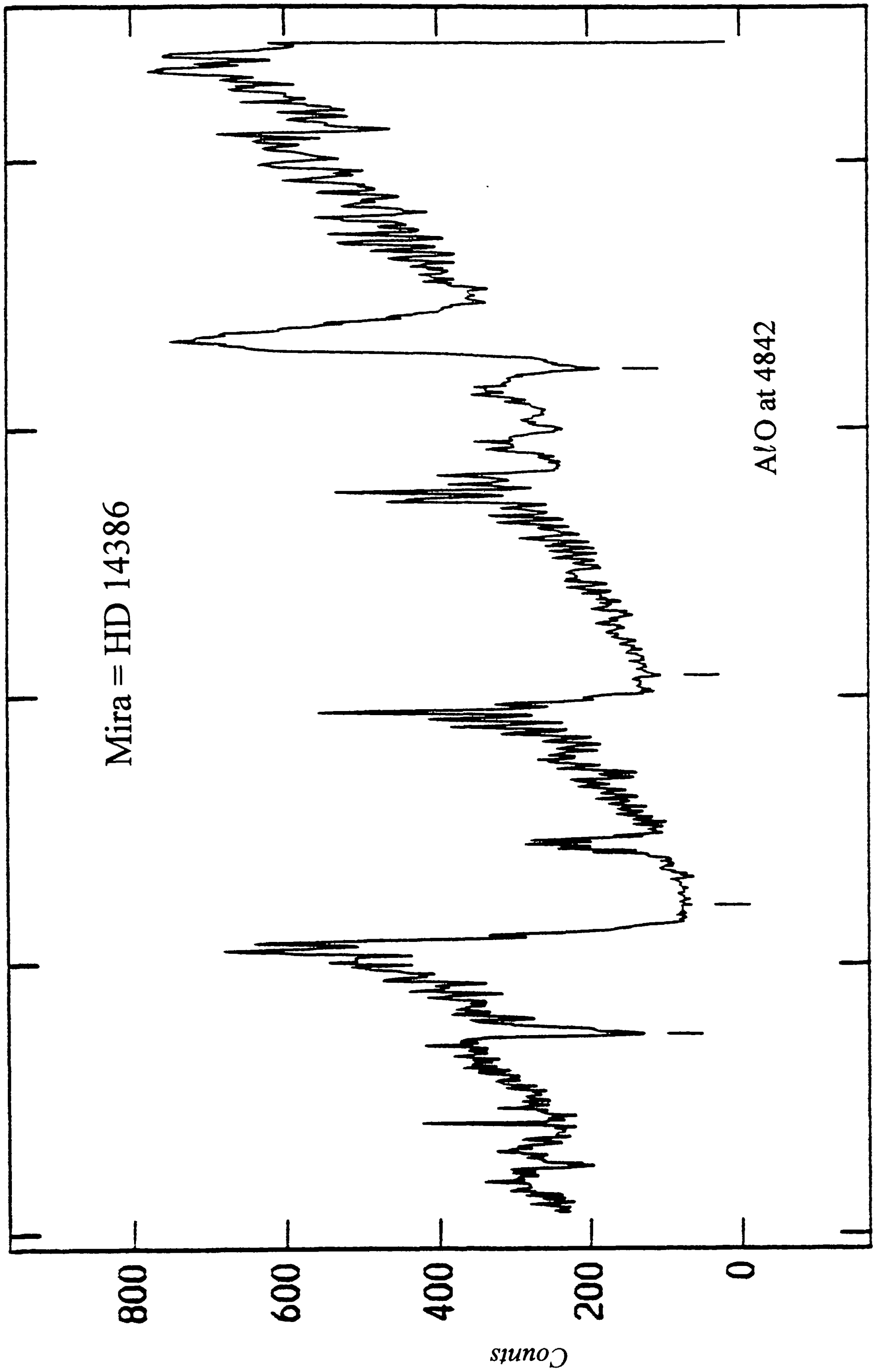

Figure 1. CCD spectrum of Mira taken in August 1996, showing the main aluminum oxide bandhead near hydrogen beta.

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