CEPHEID VARIABLES AND THE CIRCUM/INTERSTELLAR MATTER

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Abstract

Various aspects of the relation of classical Cepheids and inter- and circumstellar matter are summarized. Emphasis is given to the question of mass loss from Cepheids and to the role of these pulsating variables in revealing the recent star formation history in their neighbourhood.

KEYWORDS: *Cepheids, reflection nebulae, Stars: chromospheres*

1. Introduction

Classical Cepheids are fundamental objects in astronomy. Being regular radial pulsators, a number of relationships exist between their physical and phenomenological properties. One of them, the period-luminosity (P-L) relationship is instrumental in establishing the cosmic distance scale. In addition to their cosmological role as primary distance indicators, Cepheids serve as astrophysical laboratories for studying structure of post-main sequence stars, hydrodynamics of stellar atmosphere of supergiants, and for checking evolutionary model calculations.

Since Cepheids fall into the mass range of 4-12 $M_\odot$, their evolution is rather fast. When they enter the instability strip of the HR diagram and perform radial oscillations, they are old enough that no close connection with the remnants of the star forming cloud is expected, but still too young that mass loss characteristic of late stages of stellar evolution can be expected. Study of mass loss is, however, an interesting topic of Cepheid research for various aspects:
– The circumstellar matter results in reddening and dimming the brightness of the Cepheid, therefore a due extinction correction has to be applied when determining the absolute magnitude of the individual Cepheids.
– The effect of pulsation on the outer region and the atmospheric structure also deserves study. The question is whether the structure of the pulsating atmosphere is different from that of non-pulsating stars located at the same point of the HR diagram.
– Cepheids are unique objects in the sense that their mass can be determined

by various methods, each of them being independent of the others. When comparing the mass predicted by the stellar evolution theory with the mass values determined from various characteristics of stellar pulsation, the evolutionary masses used to be notoriously and significantly larger than the others implying a major mass loss before and/or during the Cepheid phase of evolution (see Cox (1980) for a review). This discrepancy was finally resolved when the new radiative opacities were calculated (Rogers & Iglesias, 1992), but the mass loss from the pulsating atmosphere has remained an important and unsolved issue.

2. Mass loss from Cepheids – multiwaveband studies

According to the theoretical calculations pulsation may result in significant mass loss for Cepheids, predicting mass-loss rates 7×10^{-9} and 2×10^{-7} $M_\odot$ yr^{-1} , for 5 and 7 $M_\odot$ stars respectively (Willson, 1988). Moreover, Willson & Bowen (1984) pointed out that while the star is in the Cepheid phase, mass loss could prolong its lifetime within the instability strip by as much as 5-50 times.

Is there any evidence of mass loss during or prior to the Cepheid phase? The most convincing evidence for mass loss would be the direct detection of the escaped matter. Assuming Pop. I chemical composition, about 1-2% of the mass should be in a form of heavy elements which can form dust grains. These grains could be detected in the IR-region. Several Cepheids show modest mid-IR excess, mainly at 25 μm which could arise from dust with temperatures near 150 K. For these stars the IR excesses are consistent with mass-loss rates of $10^{-8} - 10^{-9} M_\odot$ yr^{-1}, which is really a very low value (McAlary & Welch, 1986). The analysis of the IRAS data also showed that the infrared excess is independent of the pulsation period. This implies that the mass-loss process is largely independent of the size or effective temperature of the Cepheid.

If the outflowing material is hot enough, the ionized matter can be detected by observing its radio emission. VLA observations of 5 very bright Cepheids gave no positive detection at 5 GHz, only resulted in upper limits of the radio radiation, from which upper limits for the ionized mass-loss rates could be derived (Welch & Duric, 1988). These upper limits are an order of magnitude smaller than the calculated values. If Cepheids are indeed losing mass at a rate as high as predicted theoretically, the material must not be ionized.

In addition to the presence of infrared excess, stellar wind may be observed by blueshifted absorption features in lines such as Hα, Ca II H&K and Mg II h&k. The broad emissions of the Mg II resonance lines are particularly sensitive indicators of circumstellar absorption. IUE long-wavelength spectra provide sufficiently high resolution in the 2800 Å region to be able to resolve discrete absorption components. Unfortunately, there are only five classical Cepheids bright enough that could be observed by the IUE in high resolution mode (Schmidt & Parsons, 1984a). The profile of the Mg II h&k line of ζ Geminorum shows two distinct high-velocity blueshifted components near the surface escape velocity which persists for most of the pulsation cycle (Deasy, 1988). The UV spectrum of the 35-day Cepheid l Carinae indicates a mass outflow whose velocity exceeds the escape velocity at the surface. Deasy calculated a mass-loss rate of about $10^{-10}\,M_\odot\,\mathrm{yr}^{-1}$ for ζ Gem, and 3 times larger value for l Car.

3. Chromospheric emission in Cepheids

It is an obvious task to search for possible differences between the outer regions of pulsating and stable stars appearing at the same location of the H-R diagram.

As to the chromosphere, the question is whether the observable emission is due to a solar type chromosphere or it is caused by a pulsational shock that propagates through the upper atmosphere of the Cepheid. Shock-induced emission is expected during and just after the brightness maximum because this is the phase when the shock reaches the outer layers of the stellar atmosphere. In the case of a solar type chromosphere the heating is due to some mechanical flux originating in the convection zone, therefore the emission of this origin is more probable during the coolest phases of the pulsational cycle.

The profiles of the Mg II lines in solar-temperature stars are complex and composed of several components. The high-resolution IUE-spectra of Cepheids often show double emission features separated by the circumstellar absorption component (Schmidt & Parsons, 1982, 1984a,b). The general trend in the temporal variation of the total flux of h and k lines is that Mg II turns on rather suddenly and then declines during most of the cycle. The fact that some Mg II absorption components move differently from the photosphere supports the view that they originate at least several tenths of a stellar radius above it. The chromosphere of Cepheids is heterogeneous over the stellar surface and is likely composed of a number of rising and falling columns. The available data are, however, insufficient to decide whether the chromospheric activity is the result of internal convection or it is caused by a shock generated by the pulsation. In any case, for some Cepheids blueshifted chromospheric UV-lines have been observed (Schmidt & Parsons, 1984a) indicating velocities exceeding the surface escape velocity (about 100 km/s).

Hot corona can be studied by X-ray observations. At the sensitivity level of

Einstein, no X-ray emission was detected from three bright Cepheids, δ Cephei, β Dor, and ζ Gem (Böhm-Vitense & Parsons, 1983). A decade later, ζ Gem was reobserved with the more sensitive equipment on board of ROSAT (Sasselov, 1994). No X-ray flux was detected at the upper limit five times lower than previously observed, indicating that classical Cepheids do not have any hot plasma in their upper atmosphere. This means that chromospheric heating is possible in the Cepheid atmospheres but the global envelope pulsation inhibits coronal heating.

4. Cepheids in reflection nebulae

Two classical Cepheids – RS Puppis and SU Cassiopeiae – are connected with reflection nebulae (van den Bergh, 1966). RS Pup is embedded centrally in such a nebula while SU Cas is displaced from the neighbouring nebula but the Cepheid together with some other field stars illuminate the dust particles in their vicinity. These two Cepheids are particularly important because the embedding or nearby reflection nebula offers an independent means for determining their distance, therefore the P-L relation can be calibrated.

A thorough investigation of the region around SU Cas revealed additional reflection nebulae near this Cepheid and from the study of the stars in this region a loose association was discovered (Turner & Evans, 1984). The core group members are at a distance of 258 ± 3 pc and have ages of about 120 million years. The derived luminosity for SU Cas is in agreement with the luminosity obtained from the P-L relation assuming fundamental mode pulsation. It is intriguing, however, that the trigonometric parallax determined from the Hipparcos data places SU Cas at a distance of 433 pc (but the uncertainty is about 100 pc). Moreover, from their Baade-Wesselink analysis, Milone et al. (1999) concluded that SU Cas is pulsating in the first overtone mode.

The reflection nebula surrounding RS Puppis is circularly symmetric around the centrally placed Cepheid. The nebular arcs in these concentric ring structures are higher density regions of reflecting material. In his pioneering study, Havlen (1972) searched for and was able to point out the brightness variations of several nebular features due to the light echo corresponding to the 41.4 day periodicity of the stellar pulsation. The nebulosity varies with the same period as the Cepheid but with a phase delay, owing to the finite light travel time across the nebulosity. It should be emphasized that his study was based on photographic observations, and in spite of the limited accuracy and sensitivity, Havlen could follow the effect of the light echo of the Cepheid on the brightness of the dust cloud.

The phase difference between the stellar and the nebular variations depends on the linear dimensions of the nebulosity, and a comparison of the linear and angular sizes allows a geometrical determination of the distance to the Cepheid. It would be high time to repeat this study using CCD detectors which are more sensitive and allow to carry out more precise photometry.

In addition, Mayes et al. (1985) pointed out that significant variability is expected in the surface brightness distribution of the reflection nebulosity at IR wavelengths due to variable heating accompanying the effective temperature changes of RS Pup over a pulsation cycle. This infrared echo of the Cepheid variability in the surrounding nebulosity offers a similar but independent method for distance determination. Unfortunately this method has not been applied in practice in lack of dedicated far-infrared observations of this region.

The discrete rings around RS Pup must reflect the nature of the mass ejection process because it is difficult to explain such structure in terms of continuous mass-loss mechanism. The spacing between the successive rings is fairly regular: about 20,000 AU (Deasy, 1988). This is consistent with the regularly repeating phases of intense mass loss from RS Pup whose mass is about 12 $M_\odot$. Havlen (1972), however, pointed out that regularly ejected bubbles contradict the generally accepted stellar evolutionary models.

Later calculations performed by **?** showed that pulsationally driven mass loss – even if it is small – reduces the rate of the period change for all masses. According to their evolutionary models mass loosing Cepheids spend more time in the instability strip. A mass loss rate of $10^{-7} M_\odot$/yr results in 2-5 times longer crossing time for a 5 $M_\odot$ Cepheid, and the rate of period change decreases by a similar factor. Fernie (1984) compared the observed secular period changes of Cepheids with the theoretical values predicted by the evolutionary models of Becker et al. (1977). The observed changes are consistently smaller than the theoretical values which may be evidence of weak mass loss during the Cepheid phase.

5. Effects of binarity on the behaviour of the Cepheids

Presence of a companion may have important consequences on the circumstellar region around the Cepheid. It is known from the evolutionary models that epizodes of intense mass loss may occur during evolution of binary stars (Hilditch, 2001). The effects of the companion, however, have been usually neglected in the Cepheid research in spite of the fact that more than 60 per cent of the classical Cepheids belong to binary or multiple system (Szabados, 1995).

For example, it is difficult to separate the free-free emission in the mid-IR produced by the hot chromosphere surrounding a Cepheid from the free-free emission which occurs in binary systems consisting a Cepheid and a hot companion where the emission is generated by the stellar wind in the vicinity of the hot component.

Among the key issues related to Cepheids in binaries one can mention searching for traces of current or pre-Cepheid mass loss. Further important problems, e.g. calibration of the P-L relation, theoretical and observational study of period changes or possible nonradial modes excited by the companion, and search for white dwarf companions are not related to the circumstellar matter.

6. Cepheids as tracers of recent star formation history

Cepheids also serve as indicators of star formation occurred in the recent past. Here I refer to two examples. 1. Evidence of propagating star formation in the Large Magellanic Cloud based on the period distribution of Cepheids. 2. The other example shows how the motion of the interaction point of two spiral arms in M31 can be followed with using Cepheids.

About 1800 Cepheids have been analysed based on the data obtained by the MACHO microlensing experiment (Alcock et al., 1999) by comparing the theoretical and observed period-frequency distributions. The main factors that determine the period distribution of Cepheids in a galaxy are: the star formation rate, the initial mass function, metallicity of the galaxy, stellar evolution prior to and during the Cepheid phase, and the location of the instability strip. Evolutionary tracks indicate when a star of a particular mass will be at a given position in the H-R diagram. Pulsation models give the position of the instability strip, and the pulsation period of the star within the strip.

It has been revealed that a significant burst in star formation occurred one hundred million years ago. During the last 10^8 years the central region of this star formation moved from SE to NW along the bar of the LMC. From the regional period distribution of Cepheids Alcock et al. (1999) concluded that the metal content does not change along the bar of the LMC. They were also able to deduce the time scale of the star formation from the period distributions, they derived the mid-epoch and the duration of the star formation epizodes along the bar.

Taking into account the distance of the LMC (assuming a value of 50 kpc), even the velocity could be calculated at which the star formation peak has been propagating in the bar. It took about 40 million years to reach the northern end of the bar from the southern one, which can be converted into a velocity of about 100 km/s. This large velocity is an independent evidence supporting the finding that star formation was triggered tidally during the last passage of the LMC close to the Milky Way about 150 million years ago.

The star formation history in the superassociation NGC 206 in the Andromeda nebula was studied by comparing the neutral hydrogen emission map, the location and distribution of blue stars and the Cepheid variables (Magnier et al., 1997). It has been pointed out that NGC 206 is located at the intersection of two spiral arms, suggesting that the interaction between spiral arms is responsible for the enhanced level of star formation. The motion of the interaction point can be followed from the distribution of Cepheids. In that study Cepheids were used as age indicators, based on the relationship: $\log A = 8.4 - 0.6 \log P$, where A is the age of Cepheids in years, P is the pulsation period in days.

It is noteworthy that Cepheids are much more frequent in the regions south of NGC 206 where the number ratio of Cepheids/blue stars exceeds 0.5, while in the bulk of the galaxy the ratio of Cepheids to blue stars (for which $B{-}V < 0.2$ mag) is smaller than 0.2. These blue stars represent the upper part of the main sequence, where stars with ages younger than 30 million years are found.

This difference in number ratio of Cepheids to blue stars can be explained in terms of a region in which star formation is enhanced. In the southern part of M31 the star formation activity has moved during the past ~100 Myr relative to the spiral arm structure seen today. According to this explanation, NGC 206 represents the most recent phase of the enhanced star formation.

The motion of the enhanced star formation can be calculated from the displacement of the region with amply occurring Cepheids relative to NGC 206 and their age difference. Assuming a typical age of 90 Myr for the bulk of these Cepheids, 30 Myr for NGC 206, and an angular distance of 0.15 degrees between the centers of the two groups of different ages, which corresponds to ~1900 pc at the distance of M31, the relative velocity is about 32 ± 15 km/s.

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