Evidence for Pulsation-Driven Mass Loss from δ Cephei

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Abstract We found the first direct evidence that the Cepheid class namesake, δ Cephei, is currently losing mass. These observations are based on data obtained with the Spitzer Space Telescope in the infrared, and with the Very Large Array in the radio. We found that δ Cephei is associated with a vast circumstellar structure, reminiscent of a bow shock. This structure is created as the wind from the star interacts with the local interstellar medium. We measure an outflow velocity of \( \approx 35.5 \text{ km s}^{-1} \) and a mass loss rate of \( \approx 10^{-7} - 10^{-6} \text{ M}_\odot \text{ yr}^{-1} \). The very low dust content of the outflow suggests that the wind is possibly pulsation-driven, rather than dust-driven as common for other classes of evolved stars.

1 Implications of mass-loss processes in the Cepheid phase

Cepheids hold the key to the cosmological distance scale. Thanks to the period–luminosity relation (Leavitt law, [9]), they are the first rung in the ladder we use to measure the size and age of the universe. They are also a benchmark for intermediate-mass stellar evolution models. Despite their importance, however, there are still outstanding puzzles in their theoretical understanding. In particular, the mass predicted by evolutionary models is significantly larger than the mass estimated by pulsation theory, or directly measured in binary systems [4, 5].

Recent calculations [15, 2] show that the Cepheid mass discrepancy can be solved by evolutionary models including convective core overshoot and mass loss. These models can dramatically lower the predicted initial mass of a Cepheid, without preventing the star from crossing the instability strip in the so-called “blue loop” characteristic of the Cepheid phase. The main difficulty with these models is that both overshooting and mass loss rate need to be included as free parameters, rather than independently derived from stellar physics by first principles.
Our limited understanding of stellar convection is unlikely to improve in the short term, but mass loss can be directly probed with observations. Understanding Cepheid mass loss is important not only because it affects their evolution, but also for its effect on the distance scale. Standard candles can be effectively used only if their apparent luminosity can be precisely measured. Mass loss, which surrounds the star with circumstellar material, is a source of both visible extinction and infrared excess. Both factors introduce noise in the Cepheid period–luminosity relationship, and should be taken into account if we want to reach our goal of 2 percent systematic accuracy in the determination of the Hubble constant [6].

While some Cepheids are known to be associated with reflection nebulae (e.g. RS Pup), it has been difficult to prove that the circumstellar material is the result of a stellar wind. Intermediate-mass stars have a relatively short life. Such Cepheids tend to be found in regions where they are formed and where the interstellar medium (ISM) is dense. It is therefore possible that the excess emission measured in the infrared [13, 16, 1] and in the UV [5] may originate in the nearby ISM. Recent high angular resolution observations (2, 8, 14 and references therein) have revealed the presence of compact circumstellar shells around several Cepheids. The proximity of these shells to the pulsating stellar photosphere (as close as a 2–3 stellar radii) may indicate the existence of some mass loss mechanism triggered by shocks associated with stellar pulsation. Direct evidence of a large-scale mass loss process capable of explaining the Cepheid mass discrepancy has, however, eluded all observational efforts.

Our *Spitzer* observations of the Cepheid namesake δ Cephei [11] may, however, have just filled this gap. We found a large-scale structure which is best explained as an infrared bow shock resulting from the interaction of a strong stellar wind with the local ISM. Our VLA 21-cm line data [10] confirm this hypothesis and provide the first measurement of a Cepheid wind velocity as well as strong constraints on its current mass-loss rate.
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2 The δ Cephei nebula

Fig. 1 shows our Spitzer images of the δ Cephei nebula. The emission at 8.0 and 24 μm is stronger between the star and its widely separated companion (HD 213307, a B7-8 main sequence star), and is enclosed within an arched structure detected at 70 μm. This structure is aligned with the space velocity of the star (≈ 10.3 km s\(^{-1}\) and P.A. ≈ 58.3°). Flux ratios measured in different positions along the arc reveal a temperature of about 100 K. The composition, which has low PAH content with respect to the average ISM, is consistent with this structure being formed by a strong stellar wind pushing against the local ISM, as is common in stellar bow shocks.

This interpretation is confirmed by our VLA H\(^{I}\) 21-cm line mapping of the region (Fig. 2). The data reveal a large (~ 1 pc) nebula with a head-tail morphology, consistent with circumstellar ejecta shaped by the interaction between a stellar wind and the ISM. The bulk of the emission overlaps with the arc structure detected in the infrared, with a trailing tail in the opposite direction to the stellar space velocity. By fitting the H\(^{I}\) line in the velocity beams not contaminated by background emission, we derived an outflow velocity of ≃ 35.5 km s\(^{-1}\). This is the first actual measurement of the wind velocity for a Cepheid. It is worth noting that this velocity is significantly smaller than the expected escape velocity from the star (~ 200 km s\(^{-1}\)).

Based on this measurement, the dynamical age of the structure is ~ 10\(^5\) yr, consistent with the expected duration of the Cepheid phase in this star.

3 Evidence for pulsation-driven mass loss

The VLA data, combined with our infrared observations, provide strong constraints on the current mass-loss rate of the star. The total flux density of the H\(^{I}\) nebula, and detailed fitting of the 21-cm line, are consistent with a δ Cephei mass-loss rate of
\( \approx 10^{-6} \, M_\odot \, \text{yr}^{-1} \). This value may be considered an upper limit, since a fraction of the HI may have been swept out from the ISM, rather than having been lost from the star by the wind. An alternative estimate can be derived from the observed stand-off distance of the bow shock-like structure, together with ram pressure balance arguments and our measured wind velocity. This provides a lower limit of \( \approx 10^{-7} \, M_\odot \, \text{yr}^{-1} \), by adopting a conservative estimate of the local ISM density. Models show that a mass-loss rate in this range is sufficient to solve the Cepheid mass discrepancy if sustained during the time the star is crossing the instability strip.

The total flux density detected with the VLA corresponds to a total HI mass of \( \approx 0.07 \, M_\odot \). Comparison with the dust mass derived from the infrared flux detected by Spitzer implies a gas-to-dust mass ratio of \( \approx 2300 \). This value is significantly higher than the canonical ratio observed in dust-driven winds of evolved giant stars and in the ISM. This is consistent with the low PAH content measured for the \( \delta \) Cephei nebula, and is further evidence that the mass-loss process acting in this star is not dust-driven.

Additional evidence is provided by the observation that the measured wind velocity is much smaller than the escape velocity. This condition requires the existence of some regulatory process capable of lifting the stellar atmosphere, rather than accelerating the flow. It also requires that most of the energy added to the wind must be in the form of momentum, rather than heat. In evolved cool stars this momentum transfer is provided by the friction of dust grains accelerated by radiation pressure. In the \( \delta \) Cephei wind there is not enough dust to support this process and, due to the higher effective temperature of the star, the dust cannot form close enough to the stellar photosphere to effectively trigger this process. An alternative source for the required mechanical energy could, however, be provided by the pulsation of the star, a known source of strong shocks periodically crossing the stellar atmosphere and chromosphere [12], suggesting that this could be a pulsation-driven wind.

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