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INVESTIGATING BE STAR DISKS USING LONG-BASELINE INTERFEROMETRY

C. Tycner[1]

RESUMEN

Las estrellas Be forman una subclase de estrellas-B, donde éstas poseen estructuras gaseosas tipo-disco. Históricamente, la presencia de un disco fue detectado a través de líneas de emisión presentes en el espectro, o vía el exceso del IR detectado en la distribución de energía espectral originada de estas fuentes. Sin embargo, la interferometría de línea de gran base es el único método de observación disponible hoy en día, que puede ser utilizado para resolver espacialmente las regiones circunestelares de estas estrellas, usando la emisión de las líneas o del contínuo de los discos. Se revisa una muestra de los resultados interferométricos dominantes que desempeñaron un rol principal apoyando la visión actual de estos sistemas, discos planos que rotan conectados con las estrellas que a su vez rotan rápidamente, son usualmente citados como un estándar observacional. Se presentan ejemplos de trabajos y resultados observacionales de varios interferómetros incluyendo trabajos recientes. Se discuten brevemente posibles direcciones futuras.

ABSTRACT

Be stars form a subclass of B-type stars, where the stars possess gaseous disk-like structures. Historically, the presence of a disk was detected through line emission present in the spectrum, or through IR excess detected in the spectral energy distribution originating from these sources. However, long-baseline interferometry is the only observational method available today that can be used to spatially resolve the circumstellar regions of Be stars using either line or continuum emission from the disks. A sample of key interferometric results that played a major role in supporting the current view of these systems, where commonly flat, rotationally supported disks connected to rapidly rotating stars are quoted as an observational standard are reviewed. Examples of observational work and results from various interferometric instruments including recent work are presented. Possible future directions are also briefly discussed.

Key Words: stars: emission-line, Be — techniques: interferometric

1. INTRODUCTION

Gaseous disks are present throughout the universe. They have been found in environments ranging from stellar nurseries, where new stars are born from massive clouds of cold gas, to stellar graveyards where objects such as black holes or neutron stars reside. In between these extremes, however, disks around stars have been found in almost every class of stars of varying size, mass, or temperature. In particular, the disks around B-type main-sequence stars, also commonly referred to as Be, are still not fully understood and are subjects of many observational and theoretical studies.

Be stars have been investigated observationally using almost all possible techniques yielding spectral energy distributions, high resolution spectra, x-ray fluxes, spatial distributions in radio, IR, and optical. From the theoretical side many disk forming theories have also been investigated, from wind-compressed disks with and without magnetic fields to disks driven by viscosity. The review paper on Be stars by Porter & Rivinus (2003) forms an excellent basis for key references on both observational and theoretical work.

The purpose of this review is to highlight the key long-baseline interferometric studies that have shaped our current view of the Be star systems. It should be noted that the aim is not to be comprehensive, merely to establish a good starting point, especially for those who might not have read through the extensive publications related to the interferometric study of Be stars. It is now widely accepted that the Be disks are geometrically thin and that the gas within the disk obeys Keplerian motions. Rapid stellar rotation that causes pronounced photospheric oblateness and the existence of one-armed density enhancements in the circumstellar disks are also commonly accepted. It is useful to review where these accepted notions about Be stars have come from and emphasize how the observational work that

[1]Central Michigan University, Department of Physics, Mt. Pleasant, MI 48859, USA.

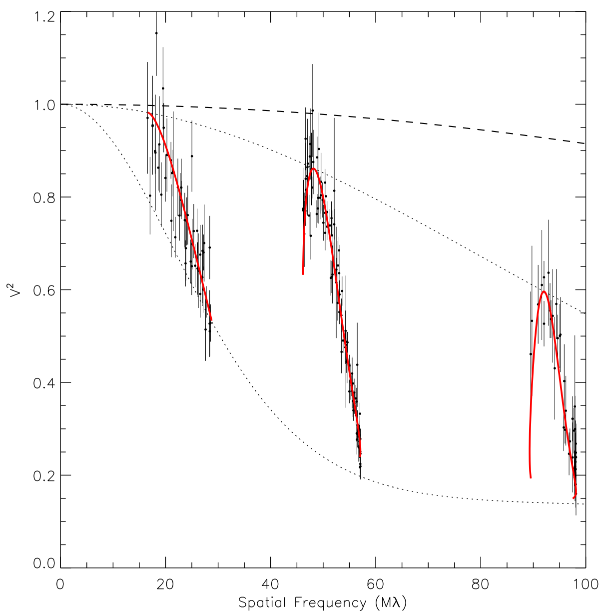

Fig. 1. Calibrated squared visibilities from the Hα channel of ϕ Per obtained at three baselines. The elliptical Gaussian model (*solid line*) fitted to all observations contains contribution from the stellar photospheric disk (*dashed line*). Model curves evaluated at the minor (*top dotted line*) and major (*bottom dotted line*) axes of the elliptical Gaussian model are also shown (figure adopted from Tycner et al. 2006).

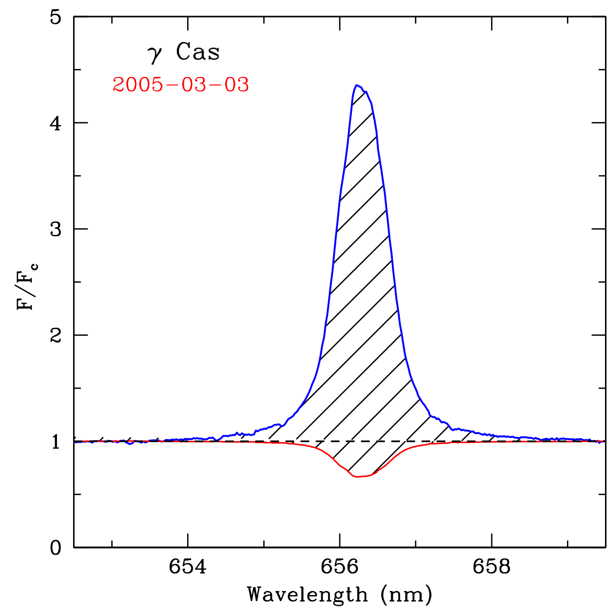

Fig. 2. Hα line profile obtained for γ Cas using the Solar Stellar Spectrograph at the Lowell Observatory. The hatched region indicates the net emission from the circumstellar disk, which is added to the underlying spectrum from the stellar photosphere (approximated by a spectrum of a normal B-type star of the same spectral type as γ Cas).

led to those conclusions is frequently based on interferometric observations that spatially resolve the disk structures on the sky.

2. SPATIALLY RESOLVING THE DISKS

A circumstellar region around a Be star was spatially resolved for the first time at radio wavelengths in the Be star ψ Per (Dougherty & Taylor 1992). Those first interferometric observations confirmed that the region responsible for the continuum and line emission in these sources is indeed much larger than the central star. Although the first radio studies suggested that the radio emission comes from non-spherical distribution of thermally radiating gas, the strong evidence for geometrically thin disks did not come until the seminal work of Quirrenbach et al. (1997) who have not only unambiguously determined the apparent 'flatness' (by detecting elliptical structures on the sky) of a number of Be stars, but showed that these are also in complete agreement with the polarization measurements.

Long-baseline interferometry is particularly suitable for detecting deviations from circular symmetry caused by a projection effect on an otherwise circularly symmetric thin disk. This is because already single-baseline measurements are capable of detecting such deviations as the projected baseline on the sky rotates during the night (due to Earth's rotation). Figure 1 illustrates how sufficiently long baselines can 'sweep' from minor- to major-axis during the night. Such interferometric observations yield very precise axial ratios of the disks which in turn can be used to place lower limits on the inclination angles i (Quirrenbach et al. 1997; Tycner et al. 2006).

Be stars are defined by the observed line emission in their spectra, especially in the hydrogen Balmer series. Hα line is the most prominent emission feature (see Figure 2) and not surprisingly has been successfully used in interferometric studies. Observing interferometrically in the Hα light not only allows probing the Hα-emitting region, which has different dependencies on the density and energetics of the gas within the disk, but also allows studying the disk dynamics at various Doppler velocities if interferometric observations are obtained across the spectral line. For example, one of the first successful interferometric observations at the Hα line were reported by Stee et al. (1995), which were used to constrain both the density and velocity relationships in the Be star γ Cas.

Regardless if the interferometric observations produce many measurements across the emission line, or just one (if the entire emission feature is recorded in a single spectral channel), one of the key issues that must be addressed is the presence of the continuum emission from the central star that always contributes to the interferometric (and spectroscopic) signal (see Figure 2). If interferometric observations are acquired across a spectral channel that contains both phase and visibility information, then one can deduce the relative asymmetries within the disk as a function of Doppler shift. This is a powerful technique for detecting over-density regions in sources with asymmetric emission lines and for constraining rotational velocities within the circumstellar disks. This is possible because different sections of the disk have different projected radial velocities and in turn contribute to different parts of the emission line. This is most pronounced in asymmetric double peaked profiles, which have been used by Vakili et al. (1998) to demonstrate the presence of one-armed oscillation within the disk of ζ Tau. Later, Berio et al. (1999) demonstrated on γ Cas that one-armed oscillation can also be detected in a system that is viewed at much smaller inclination angle, even when the line profile does not show a distinct double-peak structure (recall Figure 2).

3. RECENT RESULTS

One of the most important recent results is the interferometric evidence for Keplerian rotation, which was obtained using the Brγ emission line (Meilland et al. 2007). Although this study is based on only one source, it still represents the strongest case for Keplerian rotation within a circumstellar disk of a Be star. It is widely accepted that Keplerian rotation is common among most if not all Be star disks.

The richness and quality of interferometric observations enabled by new instruments and new reduction techniques has also enabled a direct comparison of interferometric data to more realistic disk models that no longer assume very simple geometry like uniform-disk or Gaussian intensity distributions. Most notably, Gies et al. (2007) have observed a number of Be stars in the IR and were able to constrain physical disk parameters such as disk base density and radial density exponent. Gies et al. (2007) was also the first one to show conclusively that the Hα-emitting region around Be stars is more extended than the IR continuum-emitting region and that this is most likely due to the higher opacity in the Hα light. Similar strategy has now also been applied to constrain physical parameters in a number of Be stars using the numerical model (BEDISK) of Sigut & Jones (2007), which in addition to using solar chemical composition balances all the heating and cooling rates (Jones et al. 2008; Tycner et al. 2008). However, it is important to note that the best-fit disk models that are obtained depend not only on the quantity and quality of interferometric data, but might also depend on the wavelength as well. Based on some recent tests we have performed using observations of the Be star υ Cyg in the Hα and K-band we have concluded that different values for the disk base density and radial density exponent are obtained depending which observational data set is used. We attribute this to the complexity of the χ^2 space that is used to assess the goodness-of-fit between the disk model and the observations.

4. SUMMARY AND FUTURE DIRECTIONS

The circumstellar disks around Be stars are now routinely resolved by long-baseline interferometers. As the sophistication and complexity of disk models (and in turn theories) that are tested and constrained by interferometric observations increase, it allows us to develop a better understanding of these perplexing objects. One of the key research areas to be explored in the near future is the study of the central star and the gas beyond the disk structure. The first measurements of this type have in fact been already made. For example, Domiciano de Souza et al. (2003) have reported on the apparent extreme degree of oblateness in the Be star α Eri, which has reopened the interest in the connection between rapid stellar rotation and its connection to disk formation. Similarly, the study by Kanaan et al. (2008) shows some tentative evidence for the presence of a polar jet in α Eri. In the near future, the studies that will fully describe the disk, the central star, possible jets, and any wind outflows including the interaction between the disk material and the central star, preferably constrained by observations in different wavelengths, will allow us to form a complete picture of these amazing disk-star systems.

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DISCUSSION

A. Miroshnichenko: *Do you include a contribution to the stellar flux from the continuum radiation of the disk while fitting interferometric data?:* — The output from BEDISK code does include both the continuum and Hα emission across the Hα channel. In the older analysis the continuum radiation from the central star and the disk (combined) were treated as a free parameter.

C. Neiner *Concerning the two different values of n you find in the Hα and K-band for υ Cyg, have the observations been taken simultaneously? This star undergoes frequent outbursts and the disk may have changed.* — This is an excellent point! The Hα and K-band observations were not taken at the same time (they are years apart). Therefore, this difference [between results based on interferometric observations at different wavelengths] might in fact be real. However, one must keep in mind that the "best" solution might still be one out of many. In other words, there is a very good chance that degenerate solutions exist when single wavelength data is used.

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