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THE WINDS OF THE MOST MASSIVE STARS AS VIEWED FROM LONG-BASELINE INTERFEROMETRY: MODEL PREDICTIONS

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RESUMEN

La interferometría de gran línea de base es una de las únicas técnicas capaz de proporcionar observaciones con una resolución espacial de mili-segundos de arco que son necesarias para resolver los vientos de estrellas masivas. Presentamos predicciones de los observables interferométricos de estrellas masivas basados en código CMFGEN de transferencia radiativa non-LTE y el código de Busche & Hillier (2005). También mostramos cúan dramáticamente diferentes son las imágenes monocromáticas de las estrellas más masivas cuando tienen un viento no-esférico.

ABSTRACT

Long-baseline interferometry is one of the only techniques capable of providing milli-arcsecond spatial resolution observations which are needed to resolve the winds of massive stars. We present predictions of the interferometric observables of massive stars based on the non-LTE radiative transfer code CMFGEN and the Busche & Hillier (2005) code. We also show how dramatically different the monochromatic images of the most massive stars will look when they have a non-spherical wind.

Key Words: stars: mass loss

1. WINDS OF VERY MASSIVE STARS

The most massive stars have dense winds which hide, partially or completely, the hydrostatic surface of the star from our direct view. Since such outflows are compact, and very massive stars are not found in the solar neighborhood, almost all the knowledge that we have acquired about them comes from the spatially-integrated spectrum.

Long-baseline interferometry is currently able to provide milli-arcsecond-resolution observations of massive stars (e.g., Weigelt et al. 2007). Unfortunately, this technique is rather time consuming and, for most objects, a few spatial frequencies and position angles are usually sampled. Therefore, we are still one step away from reconstructing images from such interferometric data and are left to analyze the so-called visibilities, phases, and closure phases.

The interpretation of the interferometric quantities is not straightforward in the case of massive stars. Nevertheless, they provide key constraints on the size and geometry of the region responsible for the continuum emission. When long-baseline interferometry is combined with spectroscopy, as can be done with the instruments AMBER/VLTI and VEGA/CHARA, a tremendous additional amount of information becomes available, since massive stars can then also be probed within spectral lines.

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2. RADIATIVE TRANSFER MODELING

We used the non-LTE, fully blanketed, spherical-symmetric radiative transfer code CMFGEN (Hillier & Miller 1998). The model is specified by the stellar effective temperature $T_{\rm eff}$, luminosity $L_\star$, effective gravity $g_{\rm eff}$, mass-loss rate $\dot{M}$, wind terminal velocity v_∞ and velocity law, and chemical abundances of the included species. CMFGEN allows for clumping in the wind via a volume-filling factor f.

Axisymmetric models were computed using a recently developed modification of CMFGEN which calculates the emerging spectrum in two-dimensional geometry. We refer the reader to Busche & Hillier (2005, hereafter BH05) for further details about the code, and to that paper and Groh et al. (2006, 2008) for examples of applications. In short, the BH05 code computes the 2-D source function, emissivities, and opacities, assuming that these quantities depend only on the new values of the scaled density. Any arbitrary latitude-dependent density and wind terminal velocity variations can be taken into account.

3. PREDICTIONS FROM 1-D AND 2-D MODELS

The appearance of the most massive stars and, thus, their interferometric observables such as the visibility, depend on the distance d, $L_\star$, $T_{\rm eff}$, $\dot{M}$, $g_{\rm eff}$, v_∞, and on the wavelength. Hereafter, we purposely concentrate on the spectral region around the Brackett γ 2.1661 μm spectral line in the K-band, where AMBER/VLTI data is most easily obtained.

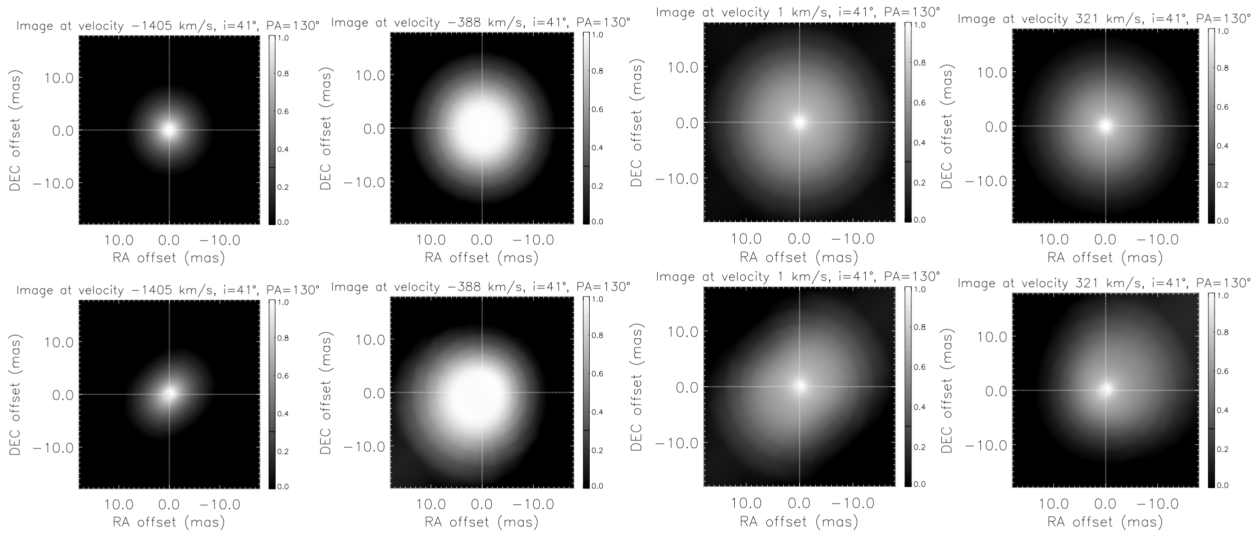

Fig. 1. *Upper row, from left to right*: Model images computed in the K-band continuum and within the Brγ line in the blue, center, and red frequencies of the line, respectively, from a spherical CMFGEN model based on the LBV Eta Carinae (see text for model parameters). *Bottom row, from left to right*: Similar to the upper row, but for a prolate model computed with the BH05 code with density contrast 4:1 from pole to equator, i=41°, and PA=130°.

Other spectral lines of interest, such as Hα, can also be studied interferometrically using CMFGEN.

Figure 1 presents CMFGEN model images based on the LBV Eta Carinae (Hillier et al. 2001), assuming $L_\star$=5×10^6 $L_\odot$, $T_{\rm eff}$=9700 K, $\dot{M}$=10^{-3} $M_\odot$ yr^{-1}, v_∞=550 km s^{-1}, f=0.1, and d=2.3 kpc. The extremely dense wind causes the presence of an extended pseudo-photosphere which, in turn, produces an extended emission halo in continuum images (Figure 1). The dense wind also causes very strong Brγ emission, which spatial extension depends on how high $\dot{M}$ is. The blueshifted part of the Brγ line, which is affected by absorption, is significantly more extended then the redshift part of the line, since absorption occurs over a larger volume than emission does (Figure 1).

Monochromatic images of massive stars become significantly more complex when a latitude-dependent wind is present. In this case, in addition to the stellar parameters mentioned above, the interferometric observables will also depend on the inclination angle i of the star and on the latitudinal variation of density and wind terminal velocity. As an illustration, the bottom row of Figure 1 presents model images computed with the BH05 code using the same stellar parameters as the above spherical model, but including a prolate density enhancement. For this example, the polar wind is 4 times denser than the equatorial wind, $i = 41°$, and PA=130°.

Due to the extended pseudo-photosphere, even the K-band continuum image is quite asymmetric, which translates to non-zero differential and closure phases whose amplitude depends on the baseline orientation on the sky. The monochromatic images become spectacular at wavelengths within the Brγ line. In the blue part of the line, due to projection effects, most of the light comes from the south-eastern hemisphere while in the red part, the emission arises predominantly in the north-western hemisphere. Such photocenter shifts cause strong, detectable signals in the differential and closure phases, which are variable as a function of wavelength. At the line center, an elongated image is seen, although much more extended than the continuum image.

Upcoming interferometric observations of a sample of very massive stars will allow us to probe their wind geometry and extension, providing key constraints on $\dot{M}$ and angular momentum loss, which are crucial for understanding Massive Star Evolution.

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