Potential Hot/Massive Star Areas of Interest for Stellar Imager

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1. Introduction

This paper is a brief summary of some major issues concerning hot/massive stars that could be resolved with *Stellar Imager* (SI), a NASA Vision Mission that would use ultra-high angular resolution at ultraviolet wavelengths to image the surfaces of stars and probe their interiors with asteroseismology (Carpenter et al. 2003, 2004).

A more comprehensive background of hot-star physics can be found in the book by Lamers & Cassinelli (1999), as well as many of the references cited below. I neglect the formation and evolutionary aspects of massive stars, and I also mainly ignore massive stars with dusty environments (such as Herbig Ae/Be stars and B[e] supergiants) which seem to be in the process of forming. For a very recent collection of "Top 10 lists" of important unresolved problems across the whole range of massive star topics, see Barbossa & Figer (2004).

2. Understanding hot-star rotation

Understanding how massive stars rotate is important for the accurate modeling of stellar evolution and computing the final chemical yields of stars (see, e.g., Maeder & Meynet 2000a). Hot (O, B, Wolf-Rayet) stars tend to be the most rapidly rotating types of stars (excluding white dwarfs and neutron stars), and many are rotating so fast that their shapes must be centrifugally distorted into oblate spheroids. Although rapid rotation in close/eclipsing binaries is measurable using light curves and radial velocity profiles, it is extremely difficult to pin down the detailed properties of *single-star* rapid rotation. (Rotationally broadened spectral lines, summed over the entire emitting surface, provide a measure of the product of the surface rotation speed and $\sin i$, where i is the inclination angle to the observer. Accurately determining i, though, is difficult even with present-day interferometry and spectropolarimetry.)

With 10 to 1000 interferometric resolution elements across a stellar disk, though, several new methods of measuring hot-star rotation become possible:

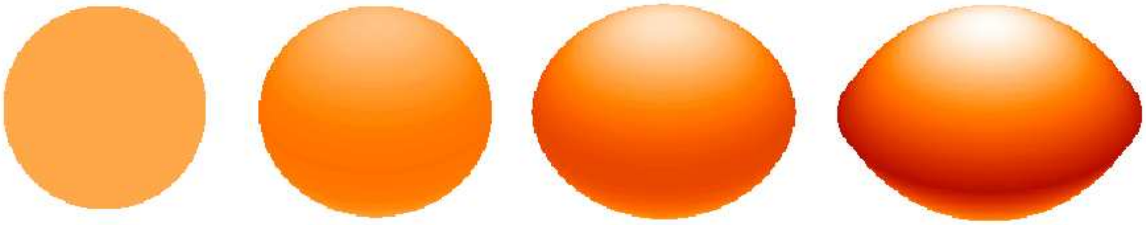

Fig. 1.— Color representation of the bolometric flux emergent from a B2 main-sequence star rotating at 0, 60%, 80%, and 99% of its critical "breakup" rotation speed (left to right) and obeying von Zeipel (1924) gravity darkening.

1. Obviously, the rotation rate can be measured directly (along with any differential rotation) by tracking features that move across the star at different latitudes. Even though hot stars are not expected to have sub-surface convection—and thus probably weaker surface magnetic activity compared to solar-type stars—there is ample evidence for rotationally modulated spots in several cases (e.g., Balona & Engelbrecht 1986; Smith et al. 1994; Reiners et al. 2000). Whether these spots are magnetic in nature is still not known.

2. The ability to measure the stellar oblateness with a high degree of accuracy provides an independent means of determining the rotation rate. This complements the surface feature-tracking method because the oblateness is sensitive to the rotation of the entire stellar interior (thus possibly giving us a better measure of the star's *total angular momentum* than feature-tracking alone could provide).

An important—but seldom directly measured—aspect of hot-star rotation is the phenomenon of *gravity darkening* (see Figure 1). A distorted gaseous star in radiative and hydrostatic equilibrium exhibits a change in its net radiative flux which is proportional to the local "effective gravity" over its surface (i.e., gravity + centrifugal acceleration; von Zeipel 1924). Thus, the equators of rapidly rotating stars become dimmer and cooler than their poles. For eclipsing binaries, gravity darkening has been measured by its inclusion in the list of optimization parameters that are varied in order to produce agreement with multi-color light curves. For single stars, the phenomenon has been modeled extensively, but only measured indirectly by, e.g., the comparison of absorption lines formed at different latitudes (e.g., Stoeckley & Buscombe 1987).

High-resolution imaging would constrain how much gravity darkening actually exists for different types of stars, and how it gradually disappears as subsurface convection eventually sets in later than the early/mid-F spectral range. Current models are still evolving (e.g., Claret 2004), and observational constraints from eclipsing binary light curves sometimes yield types of gravity darkening that are *outside* the bounds of present theoretical possibility (Djurašević et al. 2003)!

3. Disks around Be stars

Be stars are rapidly rotating, non-supergiant B-type stars that exhibit, or have exhibited in the past, emission in the hydrogen Balmer lines. The observed properties of Be stars and their circumstellar gas are

Fig. 2.— Artist's conception of the circumstellar environment of the Be star in the ϕ Per binary system (Image credit: Bill Pounds, STScI-PRC1997-39).

consistent with the coexistence of a dense equatorial disk and a variable stellar wind (for a recent review, see Porter & Rivinius 2003; see also Figure 2). The gas in the so-called 'decretion disk' is generally believed to be ejected from the star and not accreted from an external source, and the rapid rotation of Be stars has been associated with the presence of the disk since at least the 1930s. One of the longest-standing puzzles in hot-star astrophysics is the physical origin of this disk, both from the standpoint of mass supply (the winds may be too tenuous) and from the standpoint of angular momentum supply (the disks are Keplerian but the stellar surfaces are not). Also, there are many examples of stars that have exhibited alternating Be and "B-normal" phases of activity (the latter implying disappearance of the disk), with time scales of various kinds of variability ranging from days to possibly centuries.

Optical interferometry has begun to probe the broad-brush properties of a few nearby Be-star disks (e.g., Quirrenbach et al. 1997), but the low resolution only barely provides the ellipticity of the inclined disk and any large-scale inhomogeneity. Milliarcsecond resolution would allow excellent characterization of the mean disk properties (e.g., inclination, radial density structure, and thickness) as a function of spectral type and stellar rotation rate, which would provide stringent empirical constraints on the currently bewildering number of proposed theories (see below).

Also, the high-resolution imaging of non-axisymmetric structures in Be-star disks would allow a conclusive determination of what gives rise to the well-known V/R (violet/red) variability in double-peaked Hα emission lines. These variability patterns are especially puzzling because they do not rotate with the disk material, but seem to take decades to precess around the star (for possible interpretations, see Okazaki 1991; Savonije 1998). For the bright Be star γ Cas, a combination of ground-based interferometry and kinematic data from the Hα line have been used to map the precession of a supposed "one-armed" density perturbation over the last several years (Berio et al. 1999), but the features are far from well-resolved.

With SI, the much-improved set of empirically derived star and disk plasma parameters would allow us to choose handily between the 4 major proposed scenarios of disk formation (see also Bjorkman 2000 for a summary of the various ideas):

1. *Direct centrifugal ejection:* Applies only if the stars are rotating within about a sound speed ($\sim$10 km/s) of their critical break-up speeds ($\sim$500 km/s). Photospheres will show the maximal oblateness and gravity darkening (see, e.g., Townsend et al. 2004).
2. *Magnetically channeled winds:* The increased torque of a dipole-like magnetic field has been suggested as able to spin up circumstellar wind material into a Keplerian disk (e.g., Cassinelli et al. 2002; Brown et al. 2004b). Observationally, it is likely that features would appear in the disk at intermediate radii, then drift both inwards and outwards. The dipole-like flux tubes of the polar and mid-latitude stellar wind may also be discernible in UV line profiles.
3. *Impulsive outbursts:* For early-type Be stars with strong pulsational amplitudes, there is evidence that the disks are strengthened at the times of constructive interference between multiple oscillation modes (Rivinius et al. 1998, 2001). It has been suggested that the isotropic ejection of gas from a "node" on the star could lead to some material being propelled forward into orbit and some propelled backward to fall back onto the star (Kroll & Hanuschik 1997; Owocki & Cranmer 2002). High-resolution observations would certainly be able to locate the sites of these impulsive explosions and directly correlate them with any possible pulsational events in the star's atmosphere. High time resolution could also track the outward drift of the propelled gas and its smearing into a Keplerian disk.
4. *Viscous equatorial spin-up above the photosphere:* This last category encompasses several proposed mechanisms of "gentle" angular momentum addition above the photosphere, via small-scale turbulence, anomalous viscosity, radiative instabilities, or non-adiabatic pulsation coupling (e.g., Saio 1994). The main discriminator for these ideas is that the disks will be observed to persist even when none of the above perturbers are present, and that the stellar surfaces should show some kind of latitude-dependent micro/macro-turbulence.

Other unresolved issues concerning Be-star disks include the mid-latitude interaction between the wind and the disk, with the possible ablation of dense clumps as the shocked wind impacts the disk (Cranmer et al. 2000). There is also suggestive evidence for a magnetic dynamo in the star-disk interface of γ Cas (Robinson et al. 2002).

4. The "photospheric connection" between stellar variability and wind variability

Hot stars exhibit strong stellar winds that contribute significantly to the mass and energy balance of the interstellar medium. Observations of P-Cygni type UV line profiles have been made for decades, and the *quantitative spectroscopy* of hot-star winds has evolved into a reasonably accurate means of deriving fundamental stellar parameters and distances (see review article by Kudritzki & Puls 2000).

The atmospheres and winds of hot stars are intrinsically variable, and it is now accepted that in many cases time-dependent phenomena (e.g., pulsations or magnetic field evolution) in the photosphere provide "shape and structure" to the larger-scale wind (Fullerton & Kaper 1995). The direct observational confirmation of a causal connection between specific stellar variations and specific wind variations, though, has

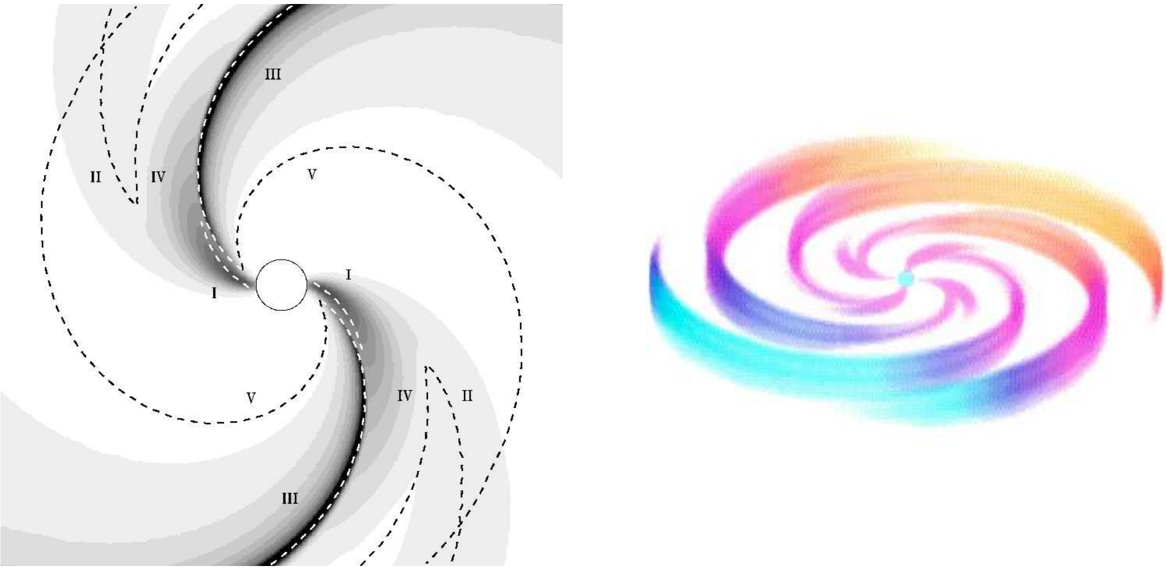

Fig. 3.— **(Left)** Grayscale representation of density perturbations in the wind of a rotating O supergiant caused by two bright spots on the stellar surface (Cranmer & Owocki 1996). Overplotted are dashed lines that trace specific dynamical features in the wind: (I) direct spot mass-loss enhancement, (II) prograde precursor, (III) CIR compression front, (IV) CIR rarefaction front, and (V) Abbott-mode velocity-gradient kink. **(Right)** Three-dimensional model of equatorial CIR density perturbations viewed from intermediate inclination (Dessart 2004).

proved elusive. For many O and B stars, it is not clear whether large-scale wind inhomogeneities are rotationally modulated (i.e., due to spots), if pulsations are responsible (as in, e.g., Mira supergiants), or if the variability occurs spontaneously in the wind.

High-resolution observations with SI would shed light on the stellar origins of wind variability. Simply seeing correlations between individual spots (no matter their physical origin) and modulations in the wind outflow would be key to understanding how hot stars affect their local environments. One suggested paradigm that can be tested is the idea that UV discrete absorption components (DACs) are caused by corotating interaction regions (CIRs) in the winds (Mullan 1984; Cranmer & Owocki 1996; Dessart 2004). Figure 3 shows the results of multidimensional hydrodynamic simulations of how bright or dark spots can lead to corotating wind variability patterns that give rise to spectral features resembling the observed DACs.

SI may also resolve the intrinsic small-scale variability of hot-star winds that arises from a nonlinear line-driven instability. Simulations have shown that tiny perturbations can rapidly grow into large-amplitude shocks that fill the surrounding volume, affect the shapes of P-Cygni profiles, and emit X-rays (for recent work see, Owocki & Puls 1999; Oskinova et al. 2004; and references therein). *Chandra* observations of hot-star X-ray emission lines have supported this paradigm for some stars, but not others (e.g., Miller et al. 2002), leaving open the question of how wind instabilities originate and manifest themselves for hot stars of various types. An improved observational understanding of the wind instability would solidify our interpretation of UV P-Cygni profiles and thus lead to improved accuracy in the determination of fundamental stellar parameters and distances.

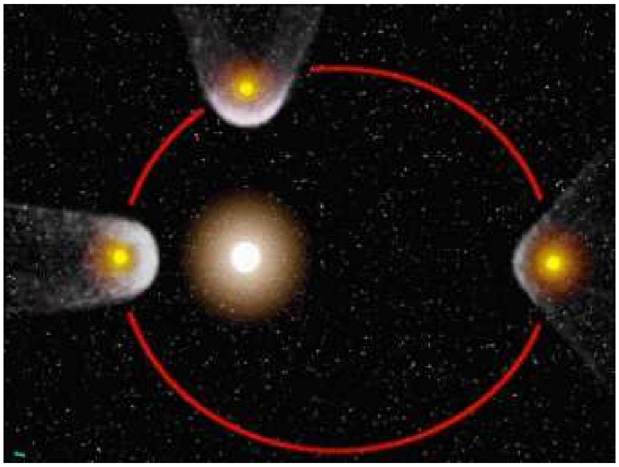

Fig. 4.— Artist's conception of the variable shape of the wind-wind collision shock in the γ^2 Vel binary system (Image credit: Henley 2004).

5. Wind-collision shocks in close binaries

Hot stars occurring in binary systems are often in such close proximity that their respective stellar winds undergo violent collisions (see, e.g., van der Hucht and Williams 1995). For supersonic winds having unequal mass loss rates and and momentum fluxes, the contact surface between the two outflows is a curved bow shock (see Figure 4). Direct imaging of these shocks is extremely difficult with ground-based instruments, and SI would be able to image their shapes with unprecedented accuracy. High-resolution UV diagnostics would complement ground-based optical and infrared studies of colliding-wind shock physics. For example, Monnier et al. (2002) studied anomalous dust formation in the hot colliding wind interface, but found the geometry to be more complicated then previously thought—making higher resolution imaging necessary.

SI images of wind-wind bow shocks would answer some nagging questions about the physics of interacting line-driven flows. For example, in some binary systems (e.g., V444 Cygni) the observationally inferred shock position seems to be at an intermediate distance between the stars, whereas their winds suffer such an *imbalance* of mass and momentum that the shock should be in contact with the surface of the weaker-wind star. Gayley et al. (1997) suggested a "radiative braking" effect by which the stellar radiation field can suddenly decelerate the incoming wind from its companion and thus keep the shock at a distance from the star. Imaging of the shapes of bow shocks in these kinds of systems would test and refine this idea.

6. Winds of Wolf-Rayet stars

Wolf-Rayet (WR) stars are believed to be the central, heavy cores of evolved O-type stars that have lost most of their hydrogen-rich outer layers as a stellar wind. WR stars have observed mass loss rates at least an order of magnitude higher than other O stars (i.e., of order $10^{-4}\, M_\odot$/yr), and the origin of these extremely dense and optically thick outflows is still not well understood. The only way that line-driven wind theory can account for such large mass loss rates is if the opacity in the lines is utilized many times (i.e., if photons multiply scatter through the optically thick outer atmosphere before they give up all of their radiative momentum to the gas); see, e.g., Gayley et al. (1995). However, other ideas exist, including fast magnetic rotation (Ignace et al. 1998) and "strange-mode" pulsations in the chemically enriched interiors (Glatzel et al. 1993). The direct imaging of the innermost emitting surface in the wind would lead to stringent constraints on these ideas.

WR winds also are observed to contain dense "clumps" with a range of scales suggesting turbulence (e.g., Lépine & Moffat 1999). The existence of these clumps has recently been found to greatly complicate the study of line-driven mass loss (Brown et al. 2004a), with the general conclusion that the presence of optically thick clumps makes it much more difficult to understand how WR winds are accelerated by radiation forces. Clearly higher resolution observations are needed in order to identify the origin and nature of these clumps, and, by inference, help clarify the physical processes responsible for the dense winds as a whole.

Some WR winds also exhibit larger-scale variability similar to the "photospheric connection" variations discussed in § 4. Even some of the most basic properties of some stars are not understood. For EZ CMa (St.-Louis et al. 1995; Georgiev et al. 1999), it is still not known if the reasonably regular variability is driven by rotation, a binary companion, or magnetic fields.

7. Luminous Blue Variables (LBVs)

LBVs are evolved, extremely luminous, and unstable supergiant stars that undergo large-amplitude wind variability. The prototypical LBV is η Car, which experienced remarkable luminosity variations between 1830 and 1860 that we now interpret as an episodic mass loss of 1–2 solar masses (see Davidson & Humphreys 1997). LBVs present some of the most frequently asked questions in in massive-star astrophysics: What causes the outbursts? What is the specific internal disturbance, and what sets its time scale? Is the observed bipolarity a result of rapid rotation, a binary phenomenon, or both? (Questions paraphrased from Barbossa & Figer 2004).

LBV stars are known to be very near the so-called *Eddington limit* in the H-R Diagram, where the outward radiative acceleration associated with free-electron scattering equals the inward acceleration of gravity. Although the potential for strong outbursts in such situations is clear, it is still not known precisely how line-driven winds (Owocki et al. 2004) and rapid rotation (Maeder & Meynet 2000b) contribute specifically to LBV mass loss. Figure 5 illustrates recent observations of η Car that indicate the gas in the inner wind is elongated along the supposed rotation axis (van Boekel et al. 2003). The relation of these—still relatively low resolution—observations to theory is evolving.

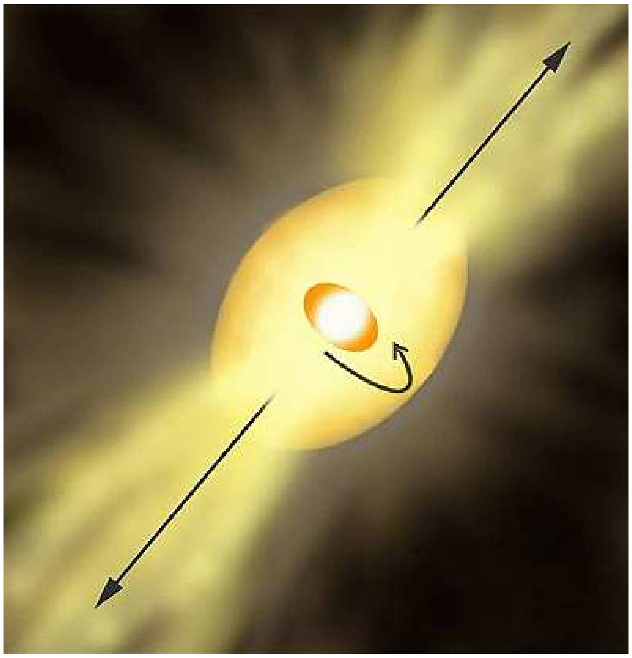

Fig. 5.— Artist's conception of the prolate inner wind surface of η Car as imaged by the VINCI instrument on the VLT (Image credit: van Boekel et al. 2003; see also ESO Press Release 31/03, PR Photo 32b/03).

8. Hot-star asteroseismology

There exist several classes of early-type stars which are inferred to pulsate strongly enough to be detected either photometrically or via line profile variations. The β Cep variables (spectral types $\sim$ B0 to B3) and the "slowly pulsating B stars" (SPBs) or 53 Per variables (spectral types $\sim$ B3 to B9) can be understood in terms of the standard Cepheid opacity instability mechanism (e.g., Dziembowski 1994), but utilizing different opacity features than Cepheids. Many classical Be stars have been deduced to exhibit nonradial pulsations (NRPs), and Kambe et al. (1993) found a correlation between circumstellar emission episodes and increased NRP amplitudes. O and B supergiants exhibit complex variability on many time scales, and it is difficult to isolate clear signatures of pulsation, rotational modulation, or intrinsic wind activity (e.g., Kaper 1993; Fullerton et al. 1996).

In no circumstances, however, have hot-star pulsations ever been directly imaged. The ability to do so with SI would allow a large number of questions to be answered about hot-star interiors, core convection, chemical mixing, and magnetic fields. Current theories of NRPs in very rapidly rotating stars are still evolving, and the imaging of how rotation affects the latitudinal profile of pulsation amplitudes would both verify or falsify certain modeling assumptions and directly diagnose the angular momentum profiles of these stars (e.g., Lee and Saio 1990; Townsend 2003). In addition, the possible "leakage" of pulsational power into the circumstellar gas could be responsible for several types of observed variations (see §§ 3–4). For example, the direct imaging of a *cause-and-effect* relationship between stellar and circumstellar features could provide the long-sought explanation for the Be phenomenon.

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