Winds that Sail on Starlight

Featured:
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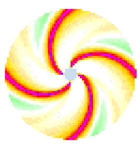

Our Sun has its flares and spots and wind, but it's a placid star compared to some. Much more massive stars tend to live fast and die young, with blue-white, intensely hot surfaces that emit energy at the rate of a million suns. These stars are so bright that their light propels stellar winds -- up to a billion times stronger than the solar wind -- at speeds up to one percent of the speed of light.

The processes by which hot, massive stars lose their substance have a strong impact on a star's evolution, and the cast-off material can also interact with other nearby stars, contribute matter and energy to the surrounding interstellar medium, and even induce bursts of new star formation.

A PUSH FROM LIGHT

The new field of radiation hydrodynamics deals with situations in which light plays an important role in the temperature and motion of gas. In the case of winds from hot stars, the flood of light is so intense that the momentum of photons striking the atoms of gas drives a high-speed flow.

"Radiative driving of matter is important in the most luminous, most energetic, and often most enigmatic objects in the universe, like quasars and active galactic nuclei," said Stan Owocki, an astrophysicist at the University of Delaware's Bartol Research Institute. "The winds from hot stars provide an ideal 'laboratory' for radiation hydrodynamics. These relatively nearby stars appear much brighter in the sky than distant quasars, allowing us to collect detailed spectra with real-time variations that reflect the dynamical formation and propagation of structures within their radiatively driven outflows. Obtaining such information is much more difficult for quasars and other very distant, exotic objects."

Together with fellow Bartol researcher Ken Gayley and recent Delaware doctoral student Steve Cranmer (now a postdoctoral researcher at the Harvard-Smithsonian Center for Astrophysics), Owocki has been developing supercomputer simulations aimed at understanding the radiation hydrodynamics of various structures that form in hot-star winds. Their research has given astrophysicists insights into the processes that govern formation of disks of gas around rotating stars, spiral wind structures, and collisions between stellar winds.

COMPRESSED DISKS

Massive blue stars typically rotate at high speeds, and astronomers have made great progress in the 1990s in understanding how rapid rotation affects a star's wind. A major breakthrough was the elegant wind compressed disk (WCD) paradigm developed by University of Wisconsin researchers Jon

Bjorkman and Joseph Cassinelli. They noted that, like satellites launched into Earth orbit, parcels of gas driven away from a rapidly spinning star should remain in a tilted "orbital plane" that brings them over the star's equator. As wind parcels from opposite hemispheres collide over the equator, they form a disk of compressed gas. This WCD model provides a natural explanation for the strong disk emission lines seen from various classes of rapidly rotating hot stars.

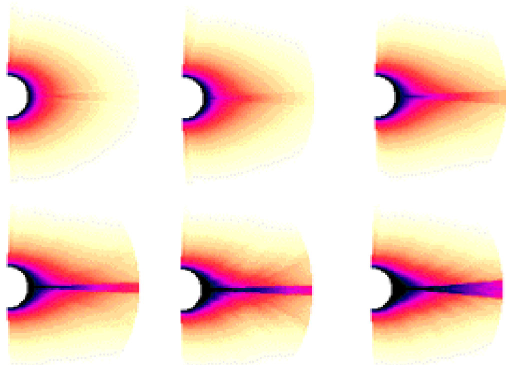

Figure 1: Wind Compressed Disks

Wind compressed disk (WCD) simulations for 200, 250, 300, (top row, left to right) 350, 400, 450 km/sec (bottom row, left to right) rotation speeds. Color indicates gas density. These models ignored gravity darkening, which may inhibit WCDs.

Owocki and Cranmer have run detailed simulations of this process on SDSC's CRAY C90, initially confirming the basic predictions of the original WCD paradigm (Figure 1). However, another aspect of rapid rotation complicates the situation. Some stars spin so fast that they flatten at the poles and bulge at the equator (Figure 2). This leads to gravity darkening -- the outflow of radiation is unevenly distributed over the distorted surface, with the polar regions brighter and the equatorial regions dimmer than they would be if the star didn't rotate.

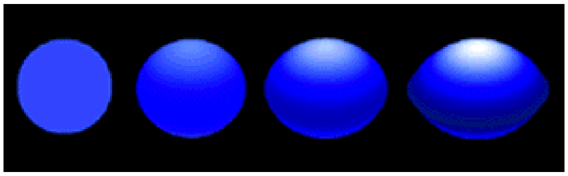

Figure 2: Flattened by Rotation

Gravity darkening in hot blue B-type stars rotating at 0, 300, 400, and 487 km/s. Colors indicate the stars' surface radiation flux.

Their more recent simulations that include gravity darkening and nonradial driving forces now indicate that such additional effects can actually inhibit formation of a WCD and even cause the bright poles to drive a denser wind than the dimmer equator. "I feel disappointed that these additional details of radiative driving turned out to work against such a beautifully simple idea," Owocki remarked. "But the general WCD paradigm is so compelling that it has since been invoked to understand circumstellar matter in a variety of other contexts. It's just a bit ironic that it may not apply to the radiatively driven stellar winds for which it was originally developed."

SPIRAL WINDS

Irregularities in a rotating star's atmosphere -- sunspots, for example -- can induce spiral wind structures as regions of compression between fast and slow outward streams of gas. These co-rotating interaction regions (CIRs) were first identified in our local solar wind (see the October-December 1996 Gather/Scatter). More than a decade ago, Dermott Mullan, another Bartol researcher, suggested that similar CIRs in the wind outflows of hot stars might explain variations of certain absorption lines in their spectra. Recent hydrodynamical simulations by Cranmer and Owocki show that any region of enhanced brightness on a hot star would generate dense, low-speed wind streams. As the star rotates, these are rammed from below by the faster wind from undisturbed regions, forming the characteristic spiral pattern of a CIR (Figure 3).

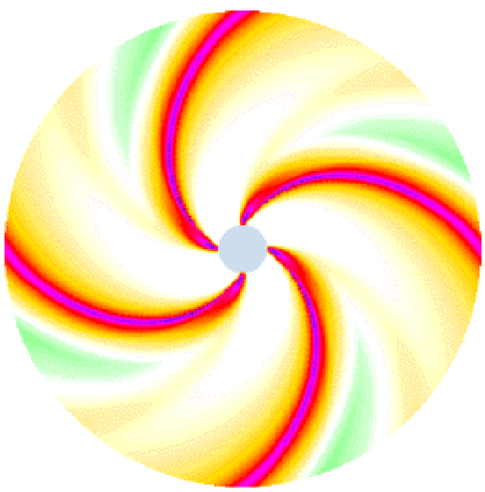

Figure 3: CIR Spirals

A simulation of co-rotating interaction regions (CIRs) in a stellar wind. Bright surface regions generate high-density, low-speed gas streams that are rammed by the faster, unperturbed wind as the star rotates, forming a spiral pattern.

"A major success here is that our simulations do produce the variable absorption line features," Cranmer said. "But we found to our surprise that the extra absorption comes not from the densest region of the spiral, as we expected, but from an extended layer with nearly uniform velocity that marks the initial response of the undisturbed wind to the slower CIR compression ahead. This is an entirely new phenomenon unique to these radiatively driven winds. In our simulations it results in spectral features that shift slowly through the line profile over time, much as we observe in real spectra."

WINDS IN COLLISION

Hot, massive stars often occur in close binary systems. Some of the more spectacular of these are Wolf-Rayet stars, which are the extremely hot cores of formerly larger stars whose wind has stripped away their outer layers of hydrogen. Spectroscopic observations indicate that Wolf-Rayet stars have particularly massive winds, generally much stronger than those of the less-evolved companion star. The collision of the two stars' winds can be complex and violent.

Gayley and Owocki modeled the binary system V444 Cygni, in which a Wolf-Rayet star and a massive blue star of spectral type O orbit each other only a few diameters apart (Figure 4). Relatively simple hydrodynamic analyses predict that the Wolf-Rayet's wind should overpower the wind of the companion star, stopping only at a shock front near the surface of the O star.

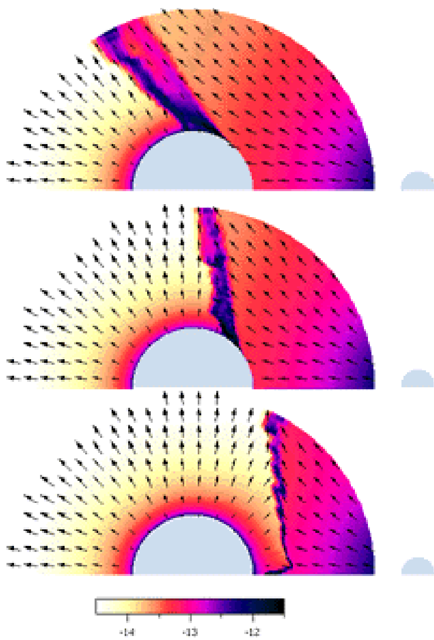

Figure 4: Putting on the Brakes

Radiation hydrodynamics simulations of the binary star V444 Cygni, showing the wind-to-wind shock front. In the three cases, the absorption of radiation by Wolf-Rayet wind material is 1.0, 2.0, and 5.0 times that of the companion star's wind, altering the effectiveness of radiative braking. Arrows are wind velocity vectors; shading represents mass density.

Gayley and Owocki's simulations include the effects of radiative momentum transfer and indicate that this can significantly alter the collision's strength, geometry, and consequences, such as production of X-rays. "Our 'radiative braking' process explains why the more massive wind does not overwhelm the weaker one," Gayley said. "The geometry of the shock front depends strongly on how well the gas in the wind absorbs radiation." Observations of this geometry as the two stars move in their orbits may lead to better estimates of the wind's radiation absorption factor and a better understanding of how Wolf-Rayet stars can propel such strong winds in the first place.

"Exploring the effects of radiation hydrodynamics requires a lot of supercomputer processing," Owocki concluded. "Generally it's a couple of hours on SDSC's CRAY C90 per model, maybe as much as five or 10 hours for the highest resolution runs I publish. But for every model that ends up in a paper, there are probably several dozen tests to explore what happens when you change boundary conditions, the force parameters, the numerical resolution, and so on. Numerical experimentation helps us determine which of the many details are the dominant effects. Supercomputers help us discover principles like radiative braking which, in hindsight, we should have been smart enough to predict without them."
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FURTHER INFORMATION

Moffat, A., Owocki, S., Fulleton, A., and St-Louis, N., "Instability and Variability in Hot-Star Winds," *Astrophysics and Space Science*, vol. 221, 1994.