Solar and Stellar Winds

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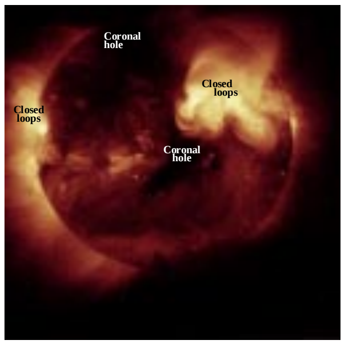
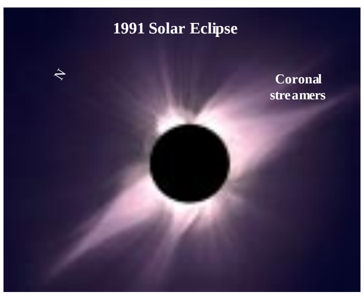
The Sun and other stars are commonly characterized by the radiation they emit.
But the past half-century has seen the discovery that the sun, and probably all stars, also lose mass through an essentially continuous, high-speed outflow or "wind".

The Solar Wind

- Early evidence that the sun might be continuously expelling plasma at a high speed came from observations of the dual tails of comets.
- One tail, made of dust slowly driven away from the comet by solar radiation, has an orientation that is tilted to the anti-sun (radial) direction by the comet's own orbital motion.
- A second tail comes from cometary ions picked by the solar wind. It's more radial orientation implies that the radial outflow of the solar wind must be substantially faster than the comet's orbital speed.

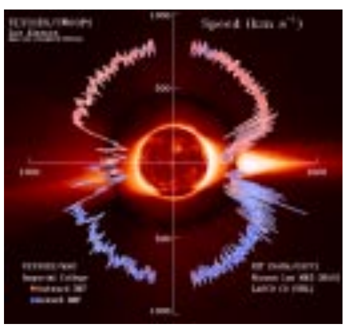
- The cause of the solar wind is the pressure expansion of the very hot (million degrees Kelvin) solar corona.
- The high temperature causes the corona to emit X-rays.
- Images made by orbiting X-ray telescopes show the solar corona has a high degree of spatial structure, organized by magnetic fields. Within closed field coronal loops, these effectively hold back the coronal expansion. But along radially oriented, open-field regions the wind flows rapidly outward, leading to a relative reduction of the plasma density that appears as a relatively dark "coronal hole".

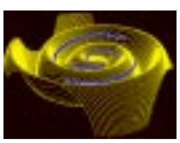




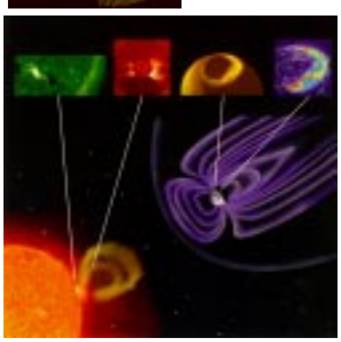
- The corona can also be observed in white light from the ground during a solar eclipse, or using "coronagraphs" with occulting disks that artificially eclipse the bright solar disk.
- Such images show the closed loops are extended outward into radial coronal streamers by the wind outflow.
- Both X-ray and white-light observations show that closed-field loops tend to occur near the equator, while open-field coronal holes are usually near the solar poles.
- But the solar wind is most directly observed *in situ* by interplanetary spacecraft with plasma instruments to measure the wind's speed, elemental composition, ionization state, and the interplanetary magnetic field (IMF).

- Coordinated interplanetary and coronal observations have demonstrated that coronal holes are the source of wind streams with a much higher speed (>700 km/s) than the typical, slower (~400 km/s) wind.
- As first to fly far out of the ecliptic plane, the *Ulysses* spacecraft has measured steady high-speed wind from polar coronal holes.

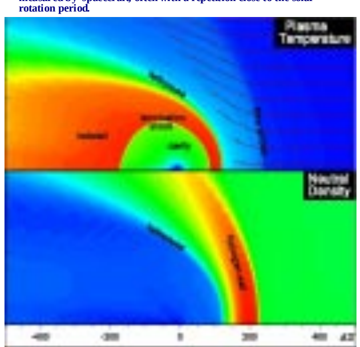




- At high latitudes the IMF has a nearly uniform polarity set by its coronal source region.
- But near the ecliptic it can repeatedly switch as the spacecraft crosses a warped, spiral current sheet surface.



- The generally lower-speed ecliptic-plane wind also shows abrupt switches to high-speed streams that originate from low-latitude coronal holes.
- The rotation of the sun brings about a collision between these high- and low-speed streams along spiral Co-rotating Interaction Regions, forming abrupt shock discontinuities in plasma conditions that are measured by spacecraft, often with a repetition close to the solar rotation period.

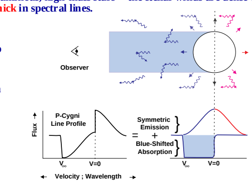


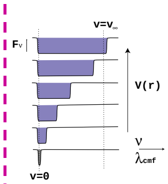
- The solar wind interacts with the earth's magnetosphere, providing a key way that solar activity can induce geomagnetic activity, and perhaps even influence earth's climate and weather.
- Finally, the solar wind blows out a "heliospheric cavity" in the local interstellar medium. The Voyager spacecraft may reach the "bow shock" of this cavity within the next couple decades.

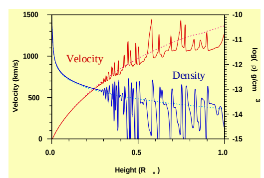
Stellar Winds

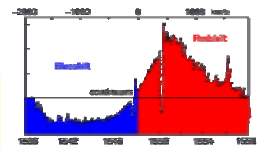
- Evidence of episodic stellar mass loss in the form of novae or supernovae has been known since antiquity. But the realization that stars could also have a continuous wind dates from the 1960's, largely from analogy with the solar wind.
- Low-density, optically thin coronal winds from solar-like, low mass, main-sequence stars can only be inferred indirectly, e.g. by X-ray observations suggesting stellar coronae.
- But for some stars -- e.g. during the Red Giant phase of a solar-mass star, or from hot, luminous, high-mass stars -- the stellar winds are dense enough to be optically thick in spectral lines.

- Lines formed by scattering of the stellar radiation within the expanding wind develop a characteristic shape -- a P-Cygni profile -- whose features provide a direct diagnostic of key wind parameters, like the wind speed and mass loss rate.
- For Red Giant stars, such profiles suggest relatively slow speeds, 10-50 km/s, but with mass loss rates up to million times that of the solar wind, i.e., ~ 10^{-8} $M_{\odot}$/yr.
- But massive stars show the strongest winds, with speeds sometimes exceeding 3000 km/s, and mass loss rates up to a billion times the solar wind, i.e. ~ 10^{-5} $M_{\odot}$/yr !
- This is large enough that, during the course of their relatively brief (~10^7 yr) evolutionary lifetime, such massive stars can be stripped of their entire hydrogen envelope, exposing a "Wolf-Rayet" star characterized by strong line emission from ions of nuclear processed elements like Carbon, Nitrogen, and Oxygen.
- For Red Giants the wind driving mechanism is not well understood, but may involve a combination of stellar pulsation, Alfvèn wave pressure, or radiation pressure on dust.

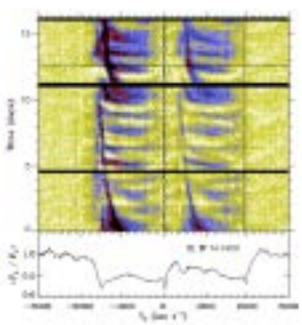




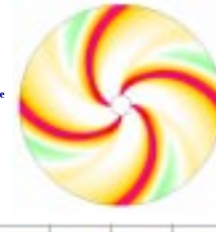


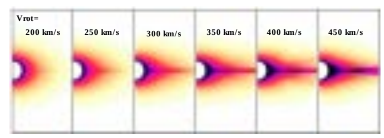


- For hot, luminous stars the driving is generally thought to stem from radiation pressure acting through line scattering. The Doppler shift of the line-profile within the expanding wind effectively "sweeps out" the star's continuum momentum flux.
- This makes the driving force a function of the wind velocity and acceleration, leading to strong instabilities that likely make such winds highly turbulent.

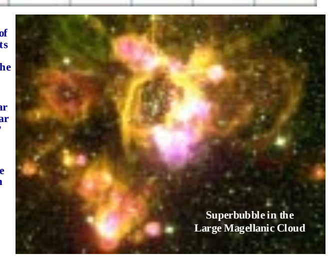


- Monitoring campaigns of P-Cygni lines formed in hot-star winds also often show modulation at periods comparable to the stellar rotation period.
- These may stem from large-scale surface structure that induces spiral wind variation analogous to solar Corotating Interaction Regions.
- The generally rapid rotation of hot stars can also lead to focusing of the outflow into an equatorial "Wind Compressed Disk".





- The large mass loss of hot-stars also represents a substantial source of energy and mass into the interstellar medium.
- Indeed, interstellar nebulae near young star clusters often show clear "wind-blown bubbles" from the many hot, massive stars.
- In particularly dense clusters, these can even coalesce into large "superbubbles".



- The compression around such wind bubbles may play a role in triggering further star formation. Some galaxies even appear to be undergoing "starbursts", with integrated spectra dominated by young, massive stars.
- Radiative driving processes similar to those occurring in hot-star winds may even be key to understanding broad-line outflows from Active Galactic Nuclei and Quasars .