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Crossing the "Yellow Void" – Spatially Resolved Spectroscopy of the Post–Red Supergiant IRC+10420

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Abstract. IRC+10420 is a post–red supergiant at the empirical luminosity boundary in the HR diagram. It has now reached a stage in its blueward evolution where increasing opacity and partial ionization destabilize its atmosphere leading to rapid mass loss. Indeed, its wind is so dense that it is opaque and hides the underlying star. We have obtained HST/STIS spectroscopy with spatial resolution good enough to separate the star from its complex ejecta with numerous arcs, knots and jet-like features. The ejecta form essentially a reflection nebula, allowing us to view the star from a range of directions. The kinematics of the ejecta cannot be reconciled with existing models with either an equatorial disk or a bipolar outflow. Therefore we propose a model with a uniform spherically symmetric outflow of gas with random, asymmetric ejections superimposed. In our model, local instabilities allow for inflowing and outflowing material to coexist.

1. A Theoretical Dilemma in the Upper HR Diagram

The most luminous red supergiants encounter a problem evolving blueward through the "yellow" or intermediate temperature part of the HR diagram due to the dramatically increasing opacity above 6000 K. If the star loses enough mass as a red supergiant, it may eventually exceed the effective Eddington Limit. But, even if the limit is not strictly exceeded, the increased opacity and partial ionization will destabilize the atmosphere and rapid mass loss will occur. This is a form of the modified Eddington Limit (Humphreys & Davidson 1994) and de Jager (1998) has called this critical region (7000 – 10000 K) in the upper HR diagram the "Yellow Void."

The intermediate–temperature stars near the upper luminosity boundary are called hypergiants (see Fig. 1). Their behavior and the evolutionary state of many of them is not understood. The most extreme example of a hypergiant in or near the yellow void is IRC+10420.

2. What is IRC+10420?

IRC+10420 is one of the few stars that define the empirical upper luminosity boundary in the HR diagram for evolved massive stars between the main se-

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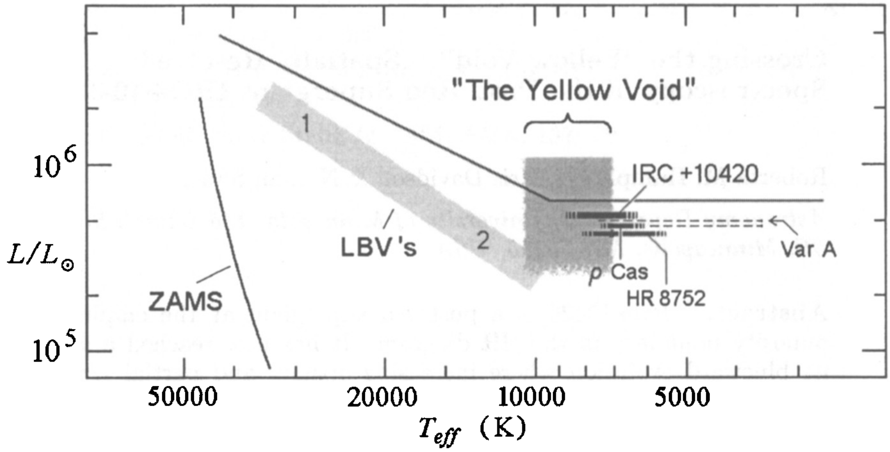

Figure 1. A schematic HR diagram showing the position of the yellow void with IRC+10420, Var A in M33, ρ Cas, and HR 8752 and their range in apparent temperature corresponding to their spectral variations. The shell episodes in Var A and ρ Cas are shown as dashed lines. Locations of the classical (1) and less luminous (2) LBV's in their quiescent state are shown as a band, also known as the the S Doradus instability strip. The solid line is the empirical upper luminosity boundary. From Humphreys, Davidson & Smith (2002).

quence and the red supergiant region (Fig. 1). It is about 5 kpc from the Sun (Jones et al. 1993) with the following parameters:

Luminosity $\approx 5 \times 10^5\,L_\odot$ (Jones et al. 1993);

Spectral Type A–F;

Mass loss rate $\approx 3 \times 10^{-4}\,M_\odot\,yr^{-1}$ (Knapp & Morris 1985; Oudmaijer et al. 1996; Humphreys et al. 1997);

Wind speed $\approx 40 - 50\,km\,s^{-1}$.

Note the extraordinarily high mass loss rate. Unlike other known hypergiants such as ρ Cas and HR 8752, IRC+10420 has a conspicuous and complex circumstellar nebula (Humphreys et al. 1997). It is one of the brightest $10 - 20\,\mu m$ infrared sources in the sky and is also the warmest known OH maser. Its apparent brightness increased substantially from 1920 to 1970 and its apparent spectral type is thought to have changed from late F to mid–A–type during the past 30 years (Humphreys et al. 1973; Oudmaijer et al. 1996). Thus IRC+10420 is our best candidate for post–red supergiant evolution near the top of the HR diagram.

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3. The Spectrum of the Central Star and the Ejecta

We obtained STIS/CCD spectra at two slit positions; one passing through the central star and several structures in the ejecta and the second slit position $\approx 0\farcs5$ south of the star in the ejecta. The high spatial resolution of STIS ($0\farcs05$ – $0\farcs1$) allows us to separate the star from its bright inner ejecta.

The spectrum of the star is dominated by strong emission in Hα, Hβ and the Ca II infrared triplet and [Ca II]. The Hα, Hβ and Ca II lines all have double–peaked profiles with a stronger blue component. Hα has remarkably broad wings presumably due to electron scattering.

The circumstellar material is essentially a reflection or scattering nebula as expected. The spatial dependence of the reflected spectrum basically allows us the see or view the star from different directions. We have measured the Doppler velocities of the reflected Hα emission at various locations along the slit and find a uniform expansion or outflow velocity of 40 – 50 km s^{-1}.

The different locations see the star from a range of directions yet the velocity difference between the two emission peaks is remarkably consistent ($\approx$ 120 km s^{-1}), the same as in the stellar spectrum. Previous work has interpreted the double-peaked profiles as evidence for a circumstellar disk (Jones et al. 1993) or a bipolar outflow (Oudmaijer et al. 1994). In either case the Hα profile should depend on the viewing direction and the projected velocities should vary with latitude. Our results require a more or less spherically symmetric outflow of the gas to explain the double- peaked profiles, contrary to what is usually assumed. The double peaks of the emission lines arise far outside the pseudo–photosphere of the opaque wind in a nearly spherical outflow.

Inverse P Cygni profiles (Oudmaijer 1995) are observed for many of the lines. To explain the evidence for simultaneous outflow and infall of material near the star, we propose a "rain" model related to the Modified Eddington Limit and the presence of the optically thick wind. The inner dense wind has a strong outward radiation force. At some radius, however, the temperature will fall below 8000 K, the effective opacity will decrease and gravity will again dominate. In that region local instabilities may cause the wind to divide or break up into a high–velocity outward gas stream and low–opacity inward–falling blobs.

Although our observations show a basically symmetrical outflow of gas, the images of IRC+10420 reveal a very complex circumstellar environment with numerous arcs, rings and knots. We therefore suggest that localized asymmetric ejections have occurred possibly due to a magnetic field and related "activity"on the stellar surface.

4. Crossing the Yellow Void

The mass loss rate in IRC+10420 is sufficiently high combined with its apparent temperature (7000 – 8500 K) to make the wind *optically thick*, in the Balmer continuum and at the blue to red wavelengths. There is no static atmosphere and the "stellar surface" is best defined as the sonic point in the flow. Consequently the observed variations in apparent spectral type and inferred temperature are due to changes in the wind and do not necessarily mean that the underlying stellar radius and interior structure are evolving on such a short timescale.

Thus from our perspective the yellow hypergiants, hidden by their dense winds, may appear to be relatively stalled on the upper HR diagram in the temperature range 6000 – 8000 K. However, if the intermediate type hypergiants are post–red supergiants on blueward evolutionary tracks, as we believe for IRC+10420, then their interiors or cores will continue to evolve, unconcerned with their external appearance. The yellow hypergiants very likely remain in this unstable state until, due to interior evolution, the underlying surface, defined as the sonic point beneath the opaque wind, becomes sufficiently hot ($\geq$ 12000 K) to shed its dense false-photosphere or opaque wind. The star would next be seen on the blue side of the void with a temperature of 12000 – 20000 K, possibly as a post-RSG LBV like the "less luminous" type in Fig. 1. With the apparent warming of its dense wind, the recent appearance of strong hydrogen emission, and a possible decline in its mass loss rate, we suggest that IRC+10420 may be *in transit across the semi-forbidden region of the yellow void.* However, we do not know whether it has just begun or is near the end of its passage. The latter is the more interesting possibility, and continued observations of this remarkable star in the next few decades may reveal its future evolution.

A much more complete discussion of these results will appear in the August 2002 issue of the Astronomical Journal.

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