ZAMS O Stars

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Abstract. The combination of large local extinction and fast evolution has resulted in few direct observations of very young massive stars. For these and other reasons, formation scenarios for the most massive stars are poorly constrained. However, new observations made at near-infrared wavelengths can better penetrate the large local extinction in young star-forming regions than traditional optical studies. Star-forming sites which contain the youngest massive stars are called Ultra-Compact H II (UC H II) regions. I outline a 2-micron spectral classification system for OB stars which may allow direct detection of the central ionizing stars of some UC H II regions. The method is demonstrated in observations of G29.96−0.02, where we have made the first direct identification of the central ionizing star in an UC H II region.

1. Introduction

What does it mean for a star to be 'zero age'? Certainly such a notion is applicable to low-mass stars because they pass through a pre-main-sequence evolutionary stage to one where the star suddenly begins core hydrogen burning. The ignition of hydrogen in its core has a quite sudden and drastic effect on further evolution of the star. This change is reflected in a new evolutionary path on the HR diagram. A 'zero-age' main-sequence (ZAMS) star has its minimum radius, its maximum mass (for single-star evolution), its bluest colour (or hottest effective temperature), and its central core possesses its peak H/He. This definition, however, breaks down when one considers stars of higher mass.

For high-mass stars, contraction occurs exceedingly quickly. In fact, for stars above $M_* \simeq 10M_\odot$, their Kelvin-Helmholtz (contraction) timescale, $\tau_{\rm KH} \propto GM_*^2/R_*L_*$, becomes comparable to their accretion (formation) timescale. The accretion, or gravitational collapse, timescale is the time it takes for the total mass of the star to collapse from the surrounding molecular cloud and onto the central star, $\tau_{\rm acc} \propto M_*/\dot{M}$. The pre-main-sequence phase seen in low-mass stars is the observational result of having a long contraction timescale, $\tau_{\rm KH} \sim$ few million years, as compared to their accretion timescale, $\tau_{\rm acc} \simeq 10^5$ yr. However, the very short contraction time of massive stars leads to an important consequence: they do not pass through any observable pre-main-sequence phase. Instead, a high-mass star will pass directly from a hydrostatic, mass-accreting, protostar,

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in which it is radiative throughout its core and envelope, to a hydrogen-burning ZAMS star once it has accreted more than $M_* \gtrsim 10 M_\odot$, no matter what its *final* mass may be (Palla & Stahler 1993). Thus, all stars with masses greater than $\sim 10 M_\odot$, and this would include all O stars, will have begun burning hydrogen well before they even reached their final mass. It would appear that not only do the most massive stars not pass through a pre-main-sequence phase, but they also never appear as true ZAMS O stars!

2. Formation Timescales for Massive Stars

In stating that there is no pre-main-sequence phase in high-mass stars we have assumed the accretion timescale will exceed the contraction timescale. If, by some means, a $60 M_\odot$ star can accrete to its final mass in 1000 years, it *would* pass through a pre-main-sequence phase, albeit a very short one ($\tau_{\rm KH} \simeq 10\,000$ yr). This fast accretion would require a mass-infall rate of $\dot{M} \simeq 6 \times 10^{-2} M_\odot$ yr^{-1}, which is not necessarily outside the range of possibilities (Churchwell 1997, and see below). Let us consider the alternate case, where the accretion to a final $60 M_\odot$ requires a fairly long time. If the rate of mass infall onto the growing massive star is slow, say the canonical rate for solar-mass stars ($\dot{M} = 10^{-5} M_\odot$ yr^{-1}; Stahler 1994), then the accretion timescale of a $60 M_\odot$ star will be greater than its main-sequence lifetime. Such a star will have burned nearly all its core hydrogen and be at the end of its main-sequence lifetime before it has even reached its final mass! The observational effects of applying such an accretion rate to the formation of massive stars has recently been studied by Bernasconi & Maeder (1996). The first and most obvious effect is it creates a hard limit on how massive a star can be created under such conditions. Other interesting effects of a low mass-infall rate outlined by Bernasconi & Maeder include: high-mass stars will be seen emerging from their parental clouds already evolved; and the traditionally used, theoretical ZAMS, which assumes $\tau_{\rm acc} \leq \tau_{\rm KH}$, is incorrect at high masses.

Is there any observational evidence that allows us to determine the accretion timescale or the mass accretion rate for massive stars? Garmany et al. (1982) noted a "rarity" of the youngest (< 2 Myr) massive stars among Galactic star populations. They suggested that massive stars were still enshrouded in their natal molecular clouds for 1 to 2 Myr. This result may have created the misperception that massive stars are still *accreting* for 1 to 2 Myr. In fact, it only says the youngest stars are *sufficiently obscured,* $A_V \gtrsim$ several magnitudes, to be undetected at optical wavelengths. Clearly, accreting, young massive stars will be heavily extinguished, but the reverse logic, that stars with large extinctions are accreting, is not necessarily true. An O star may have long ago stopped accretion and completely shed its outer circumstellar envelope, and yet be completely obscured from view. This obscuration may be due to large line-of-sight extinction, or, more likely, it may be due to patches of molecular material from the cloud in which the star recently formed. It should be noted that a more complete study of OB stars in both the Galaxy and the Magellanic Clouds by Massey et al. (1995) was unable to determine if the lack of very young massive stars wasn't just due to a selection effect in their data. Such selection effects are likely present in the original Garmany et al. study.

The Carina region (Trumpler 14 & 16) contains some of the most massive stars known in our Galaxy. These stars have inferred masses $\sim 100 M_\odot$, based on both quantitative spectroscopic analysis (Kudritzki 1980; Puls et al. 1996) and comparisons with evolutionary tracks (Massey & Johnson 1993). These stars also have ages on the order of 1 million years. Massey & Hunter (1998a, b) find numerous stars within the R136 core to have masses in excess of $120 M_\odot$ and ages on the order of 1 or maybe 2 million years. The existence of young, massive stars gives a fairly solid lower limit for the mass-infall rate, $\dot{M} \gtrsim 10^{-4} M_\odot$ yr^{-1}, which is already significantly higher than the canonical values determined for solar-mass star.

Direct observations of very young, very massive stars therefore tell us that mass-infall rates are not the same for all masses. This is further supported by theoretical considerations. For an isothermal sphere the infall rate during 'inside out' collapse, $\dot{M}$, is given by σ^3/G, where σ is the sound speed (Shu 1977). In high-mass cores, the sound speed is dominated by a nonthermal component (closely related to the magnetic Alfvén speed) and is observed to be higher in high-mass cores than low-mass cores (Myers & Fuller 1992; Caselli & Myers 1995). This relation between clump mass and sound speed leads to a higher mass-infall rate, with more-massive clumps and the formation of more-massive stars. This relation has one further important effect. While stars may span a range of $\gtrsim 100$ in mass, their formation timescales, over such a mass range, span maybe a factor of 10 (Myers & Fuller 1993). This suggests that *all stars,* regardless of final mass, form on the order of $\tau_{\rm acc} \simeq 10^5$ years (Adams & Fatuzzo 1996).

Further evidence for a high mass-infall rate in high-mass star-forming regions can be found in radio studies of molecular outflows. Bipolar molecular outflows represent an important evolutionary stage of star formation in low-mass stars (Shu, Adams & Lizano 1987). Recently, outflows have been detected in high-mass star-forming regions. These flows have been found to harbour considerably more mass and kinetic energy than those from low-mass objects (Shepherd & Churchwell 1996). The dynamical age of these outflows are similar to those seen in low-mass regions; however, the mass flux is considerably higher. It can be argued that the mass found in the outflows originates from the infalling matter that has recently accreted onto the young massive star and has been diverted outward into the bipolar jet (Churchwell 1997). These mass-outflow rates, exceeding $\dot{M} \simeq 10^{-3} M_\odot$ yr^{-1}, suggest enormous infall rates for the most massive stars at early stages.

3. Formation of a High-Mass Stars

It has been a decade now since a well-developed theory for the formation of low-mass stars was first presented (Shu, Adams & Lizano 1987). In that time, an immense amount of observational and theoretical work in the area of star formation has strengthened and refined this model. As currently understood in this 'accretion scenario', star formation begins when high-density cores form inside of molecular clouds and become dynamically unstable. As the core collapses inside out, a small hydrostatic object, the protostar, forms at the centre of this collapse. Material which falls non-radially begins to collect along the rotational equator of the collapse and develops into a circumstellar disk. Surrounding the protostar and its circumstellar disk is a more extended infalling envelope of gas and dust, which serves as the reservoir from which the star and disk system is fed. As infall continues, the protostar becomes more massive and more luminous. Eventually the protostar develops a stellar wind and bipolar outflow.

How much of this theory for the formation of low-mass stars can be applied to high-mass star formation? Massive stars acquire large luminosities very early in their formation. Their radiation pressure may serve to reverse further infall (Wolfire & Cassinelli 1986) and disrupt the surrounding circumstellar material serving as a mass reservoir. Despite these physical differences between high- and low-mass stars, observational evidence suggests that the mechanisms involved in the formation of massive stars may be surprisingly similar to those in low-mass star formation. For example, outflows are now known to exist in high-mass star-forming regions just as in low-mass star-forming regions (Shepherd & Churchwell 1996). What drives outflows from either low- or high-mass young stellar objects (YSOs) is not entirely understood, but they may require enhanced equatorial material (disks). The formation of a disk is a direct and necessary result of the collapse of a dense molecular cloud with any net angular momentum (Terebey, Shu & Cassen 1984). Disks around low-mass young stars have been directly observed (Lay et al. 1994). In the high-mass YSOs S106 and BN, there is strong evidence that high-density material is closely surrounding these stars, and both show bipolar winds, perhaps driven through rarefied polar regions of the young star's circumstellar envelope (see Drew 1998). In fact, arguments can be made that disks are perhaps required in order to continue feeding mass onto a young massive star (Jijina & Adams 1996). Spherical infall is almost entirely prohibited due to the large radiation pressure of the young massive star (Wolfire & Cassinelli 1986). However, it may be more easy for infall to occur to the disk, first. Then, as the disk grows, instabilities develop which create episodes of catastrophic accretion onto the star from the disk (Adams, Ruden & Shu 1989).

At this very early stage of evolution, the young, massive star is entirely surrounded by a fairly dense, opaque envelope. If the mass-infall rate is not too extreme (see discussion in Churchwell 1997), the young star will ionize a high-density ultra-compact H II (UC H II) region inside this envelope. These objects are easily detected at radio wavelengths (Habing & Israel 1979). The number density of UC H II regions found in the Galaxy through radio and mid-infrared surveys suggests this stage lasts on the order of 10^5 years (Wood & Churchwell 1989; Comeron & Torra 1996), and they have linear diameters ≤ 0.1 pc (Churchwell 1993). As the dusty H II region expands beyond this diameter, mass infall will have ceased, as the star and its circumstellar environment become further de-coupled and separated. The end of the UC H II-region phase, $\tau_{\rm UC} \simeq 10^5$ yr, also must mark *the end of the accretion phase in high-mass stars.* However, we cannot rule out that accretion could have ended considerably sooner than this time, that is to say $\tau_{\rm acc} \leq \tau_{\rm UC}$. It is at the end of this stage, $\tau_{\rm UC}$, that one will find the youngest of the most massive stars just emerging from their birth cocoons.

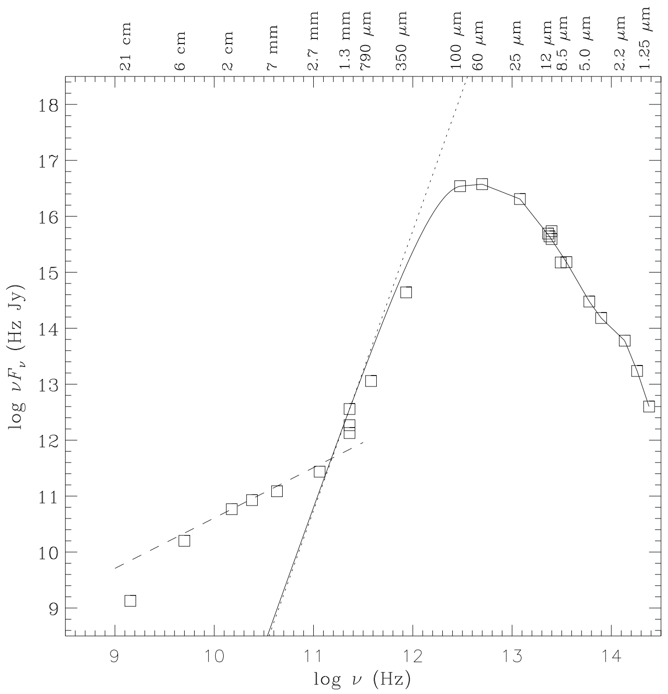

Figure 1. The spectral-energy distribution (SED) of the UC H II region G29.96−0.02 (from Watson et al. 1997).

4. Ultra-Compact H II Regions

Thus far, all information about UC H II regions has been gathered by observing the emission detected from the gas and dust surrounding the central star. In Fig. 1 we show the spectral energy distribution (SED) for the UC H II region G29.96−0.02, from Watson et al. (1997). All UC H II regions look nearly identical on such a plot. UC H II regions are dominated by free-free emission longward of a few mm ($S_\nu \propto \nu^{-0.1}$), due to high-density ($n_e \geq 10^5$ cm^{-3}) ionized gas. UC H II regions are further distinguished by a huge luminosity in the far- and mid-infrared, consistent with a very cold Planck temperature ($T \simeq$ 25–30 K) from a massive, $\gtrsim 10^4 M_\odot$ dust shell (Churchwell et al. 1990). Their high luminosities and unique mid-infrared flux distributions make them easy to detect using IRAS broad-band flux ratios (colours) (Wood & Churchwell 1989; Kurtz et al. 1994).

The three rightmost points in Fig. 1 represent the JHK bands. The thermal temperature necessary to heat dust to radiate at these wavelengths is near the dust destruction temperature. For this reason, this is the wavelength region where light coming directly from the star's photosphere may first be detected. However, while thermal dust emission is fading in this wavelength range, dust extinction is quickly increasing. At 2μm, extinction is reduced by more than a factor of 10 from the visible ($A_V/A_K \simeq 10$); at 1 μm, the advantage is only a factor of 3. When one is considering sightlines to stars with *several tens* of magnitudes of visible extinction, the difference between observing at 2μm and 1μm becomes substantial. It was for this reason that we developed a spectral-classification system at 2μm (Hanson & Conti 1994; Hanson, Conti & Rieke

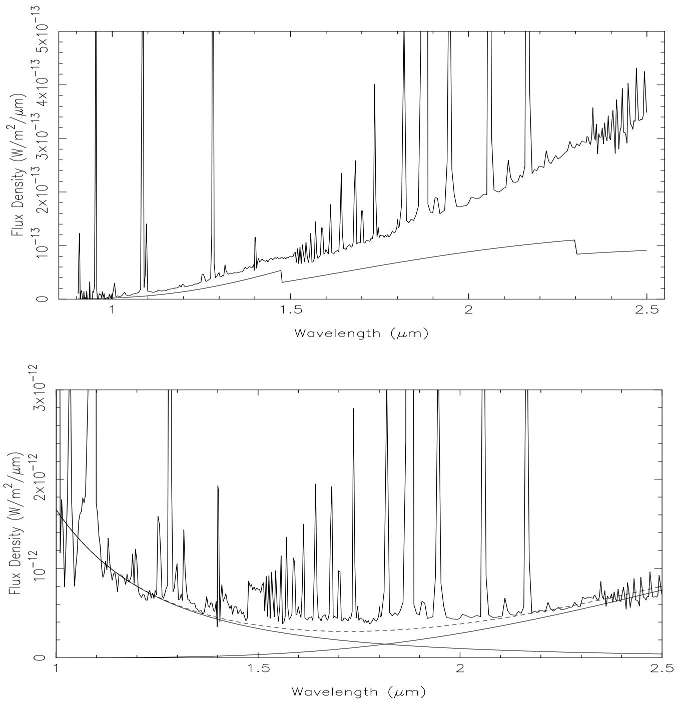

Figure 2. Top panel: observed spectrum of G45.12+0.13; the lower line shows the estimated free-free contribution. Bottom panel: extinction-corrected spectrum after removal of the free-free component. The blue sloping line represents a simple model for the starlight while the red sloping line is for a grey-body law for the local dust; the underlying star in this UC H II region is essentially impossible to detect directly. (From Lumsden & Puxley 1996.)

1996). The setback of a 2-μm classification system is that hot dust, at a temperature of $T > 1500$ K, may still dominate the flux in some of the youngest systems (Hanson et al. 1997; see also Conti & Blum 1998). Also, if the young star sits in a high-density H II region, free-free emission will produce a bright background against which the star will be more difficult to detect.

Contamination from free-free emission is illustrated by the near-infrared spectrum of the UC H II region G45.12+0.13 obtained by Lumsden & Puxley (1996). They show that approximately half the flux in the 1- to 2-μm range is attributed to free-free emission. In the lower panel of Fig. 2 the free-free component has been subtracted from the observed flux, and the difference corrected for extinction (the blue stellar flux is now rising to the left); there is still an additional excess flux longward of 1.5μm. Lumsden & Puxley attribute this emission to thermal dust. At wavelengths shorter than 1.5μm, the extinction is simply overwhelming, yet longward of 2μm the free-free and thermal dust emission dominate the continuum. This wavelength region, lying in the near-infrared H- and K-band, was what Peter Conti and I used to refer to as "between a rock and a hard place." Regardless, this spectral range remains the best available for directly detecting the stellar photospheres of deeply embedded young stars,

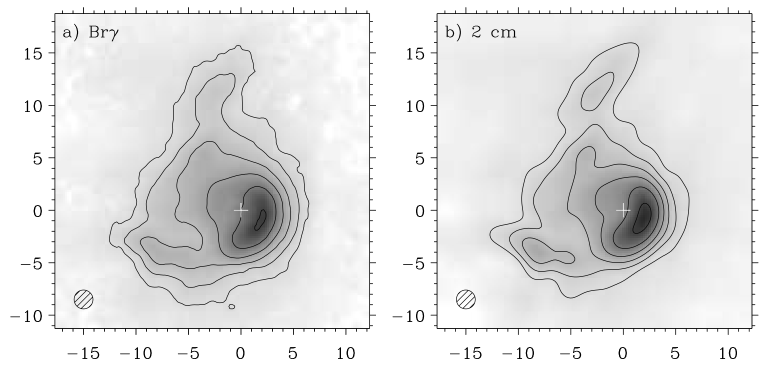

Figure 3. Left: Brγ image of G29.96−0.02, with the position of the ionizing source indicated. Right: 2-cm continuum image, smoothed to resolution of the Brγ image, showing the position of the ionizing source. In the near-infrared image the stellar source is only just resolved from the strong free-free emission peak to the right. Figure taken from Watson et al. (1997).

including the deeply embedded ionizing stars of UC H II region. It should be possible, depending on the extent of free-free and dust emission and the line-of-sight extinction, to detect the central ionizing sources of *many* UC H II regions, but *not all.* Detection will require near-infrared spectroscopy with relatively high resolution ($R > 1000$) and signal-to-noise (S/N > 100), in particular to overcome the diluting effects mentioned above.

4.1. The Central Ionizing Star of G29.96−0.02

G29.96−0.02 (G29) is a well studied ultra-compact H II region. It was first mapped in the radio by Wood & Churchwell (1989) and found to have a remarkable cometary structure (see Fig. 3). About 20% of all UC H II regions mapped thus far show a similar cometary structure (Kurtz et al. 1994 and references therein). UC H II regions frequently lie behind huge line-of-sight extinctions, rendering them unobservable even at near-infrared wavelengths. However, the line-of-sight extinction toward G29 is not so prohibitive, with 'only' $A_V \simeq 25$ ($A_K \simeq 2.5$). Watson et al. (1997) obtained deep *J, H,* and *K* imaging of the G29 field. They carefully *removed* the contributing flux from the free-free emission in the *H*- and *K*-band images. This more clearly revealed a fairly bright, 'blue' star, located at the focus of the cometary structure seen in the radio and Brγ emission. The position of the star is shown as a white cross in Fig. 3. When accurate *J, H*, and *K*-band colours are obtained, intrinsically blue stars ($T_{\rm eff} \geq 10\,000$ K) can be separated from cool giants and supergiants ($T_{\rm eff} < 5000$ K) on a *JHK* colour–colour plot, regardless of line-of-sight extinction (see Hanson et al. 1997). After correcting for extinction and estimated distance, the near-infrared magnitudes and colours of the central source in G29 was found to be consistent with an OB star (Watson et al. 1997).

An important morphological aspect of the G29 region is that the very bright nebular knot detected in the radio and infrared is *not centred on the star* (Fig. 3).

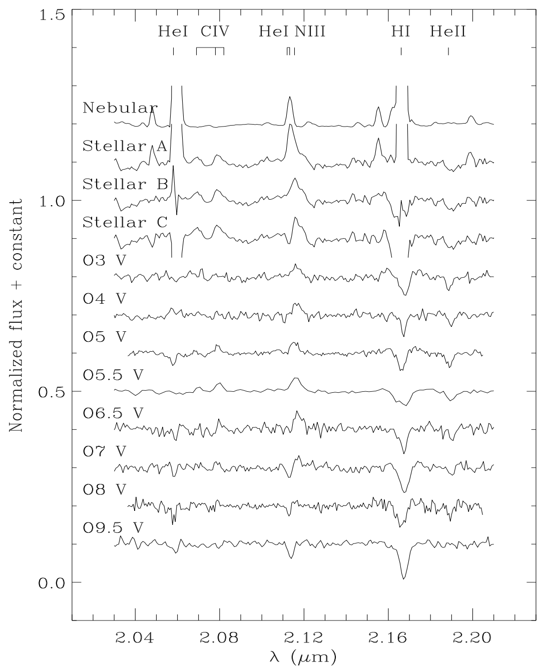

Figure 4. *K*-band spectra of G29.96−0.02. At the top is the extracted spectrum of the bright nebular peak to the SW of the stellar source. 'Stellar A' is the stellar source without nebular correction; Stellar B has the optimum nebular corrections; 'Stellar C' is over-corrected (note the over-corrected nebular features of He I at 2.058 μm and Brγ at 2.166 μm). *K*-band spectroscopic standards from Hanson et al. (1996) are also shown.

If this had been the case, the spectrum would likely be dominated by free-free and thermal dust emission, as shown in the G45 spectrum in Figure 2. Despite the angular distance between the star and the bright nebular knot, strong nebular features were still detected at the position of the star in its 2-μm spectrum. Figure 4 (from Watson & Hanson 1997) shows the raw, uncorrected spectrum of the point source, labeled 'Stellar A'. The spectrum labeled 'Nebular' was taken at the Brγ peak and scaled to match the nebular features in the 'Stellar A' spectrum. The spectrum labeled 'Stellar B' is our best effort at removing the nebular contamination using the scaled nebular spectrum. The free-free emission is contributing about 20% of the flux at 2μm. 'Stellar C' shows the stellar spectrum over-corrected for nebular emission. Even with its over-corrected nebular component, 'Stellar C' still exhibits a broad emission feature at ~2.115μm, which is N III originating from the star. Further confirmation that we have detected the stellar photosphere is provided in the strong stellar C IV features at 2.069μm and 2.078μm and He II at 2.1885μm. The ionizing star of G29 looks to be kO5–O6 (*K*-band classification; see Hanson et al. 1996). Typical O-star spectra are shown as comparisons in Fig. 4.

4.2. Previous Analyses of G29.96−0.02

Simpson et al. (1995) and Afflerbach et al. (1997) have modelled the far-infrared emission lines of G29 and found best fits with ionizing stars that have effective temperatures cooler than 36 000 K. But we now *know* the temperature of the stellar ionizing source of G29: it's an intermediate O star, with an effective temperature between 41 000 and 44 000 K. We could allow for $T_{\rm eff}$ as low as 38 000 K (an O8 star) and there is evidence, too, that the canonical temperature–spectral-type scale is too hot (Harries & Hilditch 1998; Hubeny 1998). However, the lack of agreement is disturbing. Perhaps G29 is not a good choice for mid-infrared analyses? G29 shows a fascinating cometary morphology which could be due to motion of the star relative to its parental cloud, creating a bow shock (Van Buren & Mac Low 1992), or it may have entered a champagne-flow stage (Lumsden & Hoare 1996). A successful analysis of G29 may require a more complex nebular model which takes into account the region's non-spherical geometry and explores a large range of ionization parameters. Improved stellar-atmosphere models which properly predict variations in stellar opacities in high-metallicity ionizing stars, particularly over the ultraviolet flux range which governs the relative ionizations of the observed elements, are also critical for a proper nebular analysis. Clearly, having direct detections of the central ionizing sources in more UC H II regions would be useful.

Cometary morphologies are seen in about 20% of all UC H II regions (Kurtz et al. 1994). Other morphologies seen in UC H II regions also suggest that the central star may be currently breaking out of its cocoon. Will we be able to obtain spectra of the central ionizing sources for all of these sources at 2μm? I am currently exploring this idea. The observations, however, are difficult. The radio maps have high spatial resolution, which makes the separation between star and H II region appear deceptively large. For a majority of the cometaries, the stellar source may be visible at 2 microns, but be too spatially blended ($\lesssim 1''$) with its nearby dense envelope of gas and dust for observations from the ground. Either adaptive optics, to spatially resolve the central point source from its bright extended cocoon, or spectra at extremely high signal-to-noise, to detect the diluted stellar photospheric features, will be needed. In most cases, both techniques may be needed.

5. Final Comments

It would appear that 'zero age' is perhaps a misnomer when used to describe very young massive stars ($M > 40 M_\odot$). Unless $\dot{M} \gtrsim 10^{-3} M_\odot$ yr^{-1} (which may certainly be the case), massive stars have been burning hydrogen, ionizing H II regions, creating wind bubbles, and essentially *evolving* since well before they achieve their final mass. The term 'zero age', or ZAMS, perhaps better represents that stage in evolution when the star, having reached its final mass, is seen at its maximum main-sequence effective temperature and minimum radius. This definition could be applied to ZAMS stars of all masses. This said, however, the theoretical ZAMS, based on instantaneous hydrogen ignition at a given mass, will not be the same as the observed ZAMS at very high masses. The observed ZAMS, using the above definition, probably lies to cooler effective temperatures and its exact position depends on the timescale $\tau_{\rm acc}$. The accretion timescale is thus critical to the development of a coherent theory for massive-star formation, yet it remains poorly constrained.

Observations of UC H II regions are important for constraining the accretion timescale in high-mass stars. For more than 2 decades, the study of the gas and dust from these sources at radio and mm wavelengths has yielded the best information on the early stages of massive-star formation and evolution. However, recent instrumental advances now allow us to extend our observations to slightly shorter wavelengths. Through the use of deep near-infrared imaging and high-resolution, near-infrared spectroscopy, we can search for and directly detect very young, very massive stars while they are still heavily buried within their birth cocoons. Direct observations of massive stars at this young age, which had previously been entirely inaccessible, will allow new questions to be answered concerning the formation and early evolution of massive stars. For the vast majority of UC H II regions, their central star (or stars!) will remain directly undetectable regardless of the wavelength. However, I am optimistic that at least some UC H II regions may be dispersed just enough that their very young central stars may be directly detected at 2μm. What is useful about detecting O stars powering UC H II regions is then we know they are very young, bootstrapping from the approximate age of the UC H II-region phase ($\sim 10^5$ years). Determining the age of young O stars to an accuracy better than $\sim$0.5Myr is simply not possible if we rely on evolutionary isochrones.

An important future goal is to detect the youngest of the most massive stars directly, for subsequent quantitative spectroscopic analyses. This programme will require quantitative analyses to be extended to the near-infrared. Both in an observational and a theoretical sense, this is only now becoming realized. I and others are currently obtaining high-resolution, high signal-to-noise spectroscopic observations of O stars in an effort to identify important diagnostic lines throughout the near-infrared wavelength region. Furthermore, efforts are now being made to include near-infrared line syntheses in stellar-atmosphere codes (Najarro et al. 1994; Schaerer et al. 1996). The direct analysis of ZAMS O stars and their physical conditions at early evolutionary stages promises to be an exciting new direction of research that will help us better understand how the most massive stars form.

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Discussion

Kaper: I'm interested in the bow shocks; I have a colleague at ESO who models these with hydro codes, and he gets a shock as soon as you have an O-star wind blowing against a molecular cloud. If you add some relative velocity you create a bow shock. How do you think you get such a shock?
Hanson: You just described it! There's been this problem of how you get ultracompacts to live as long as the statistics suggest ($\sim 10^5$ yr). About 5 years ago one of the best suggestions, by Mac Low and Van Buren, was simply that if you move the star relative to the cloud you'll retain a high-density environment much longer, even though the cocoon may've blown away. Now I think that's actually happening in some situations, but it doesn't explain all of them.
Kaper: But then it doesn't necessarily put a constraint on the age of the stars?
Hanson: I can't say anything about the age of a star. The only thing you can say now is, what is the timescale for it to leave the cloud? For small (≤ 0.1 pc), dense ($n_e \geq 10^5$ cm^{-3}) UC H II regions, the timescale must be very short – a few times 10^5 yr. For tenuous bow shocks created by runaway OB stars, they might be maintained for millions of years.
Drew: There's an alternative view for G29.96−0.02, the 'blister/champagne' model. Recent high-resolution work by Stuart Lumsden and Melvin Hoare has, if anything, come down in favour of this, rather than bow shocks.
Hanson: Yes, there the density's not the same all the way round, and you get blow-out on one side. In fact, my co-author in this work, Alan Watson, prefers the 'champagne' model. Since I don't work on the models myself, I've accepted what the bow-shock people say. The velocities they get from radio recombination lines are in better agreement with a bow shock than with 'champagne' – I guess it hasn't been sorted out yet. Thanks for bringing that up.
Najarro: Some of the shapes you've shown look very much like the 'pistol' feature at the Galactic centre, and most of us think that that nebula is the result of an LBV which erupted around a million years ago. What is the mass of your nebulosity? At the Galactic centre there's around $10 M_\odot$. Can you measure the recombination-line radial velocities and compare them with the radial velocity of the star in G29.96−0.02?

Hanson: Typical dust masses for UC H II regions are $\gtrsim 10^4 M_\odot$. The radial velocities range from 85 to 115 km s^{-1} across the G29.96−0.02 region. Those velocities 'smear' spatially across the nebula, which is what supports the idea of a bow shock. The stellar velocity is not known. Since we've identified stellar features at 2 μm, it should now be possible to obtain the stellar velocity.

Maeder: You've been speaking about the accretion rate. There are *two* accretion rates: one from the molecular cloud onto the disk, and the second from the disk onto the star. It's not clear which one you're observing, and they're not necessarily the same, as there can be a long delay between accretion onto the disk and accretion onto the star.

Hanson: What I'm told is that the situation is very unstable if the disk is much more massive than the central star. Over longer timescales, therefore, at least half the (disk) accreted mass has to be going onto the star – you can't build up lots of mass into the disk with a substantially smaller accretion onto the star. The rates have to be more or less the same.