NEAR-INFRARED SPECTROSCOPY OF G29.96–0.02: THE FIRST SPECTRAL CLASSIFICATION OF THE IONIZING STAR OF AN ULTRACOMPACT H II REGION

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ABSTRACT

We have obtained the first classification spectrum and present the first direct spectral classification of the ionizing star of an ultracompact H II region. The ultracompact H II region is G29.96–0.02, a well-studied object with a metallicity value roughly twice that of the Sun. The near-infrared K-band spectrum of the ionizing star exhibits C iv and N ii emission and He ii absorption, but lines of H i and He i are obliterated by nebular emission. We determine that the star has a spectral type of O5–O7 or possibly O8. We critically evaluate limits on the properties of the star and find that it is compatible with zero-age main-sequence properties only if it is binary and if a significant fraction of the bolometric luminosity can escape from the region. G29.96–0.02 will now be an excellent test case for nebular models, as the properties of the ionizing star are independently constrained.

Subject headings: infrared: stars — ISM: H II regions — ISM: individual G29.96–0.02 — stars: early-type

1. INTRODUCTION

Ultracompact (UC) H II regions are formed by massive stars still embedded in their natal molecular clouds. They are luminous and relatively easy to detect throughout the galaxy at far-infrared and centimeter wavelengths (Wood & Churchwell 1989). As such, they hold great potential for the study of the formation and properties of massive stars in different environments and at different metallicities. However, the many magnitudes of extinction to these objects have hindered their study; until recently, the stars have had to be studied by their indirect and uncertain effects on the interstellar medium (ISM).

In this Letter we present the first near-infrared classification spectrum of the ionizing star of an UC H II region and directly derive narrow limits on its effective temperature by comparison with the stellar atlas of Hanson, Conti, & Rieke (1996). The UC H II region is G29.96–0.02, a well-studied object with a metallicity value roughly twice that of the Sun (Simpson et al. 1995; Afferbach, Churchwell, & Werner 1997). Our work is complementary to that of Watson et al. (1997), who directly measured the extinction and intrinsic magnitude of the star using imaging in the radio and near-infrared and simple nebular physics. Combining these results, we are able to place the star on the H-R diagram with a high degree of reliability.

Our work motivates a critical reevaluation of the conclusion of Watson et al. (1997) that the ionizing star of G29.96–0.02 shows evidence for the evolution predicted by Bernasconi & Maeder (1996), and our independent constraints on the properties of the ionizing star will provide an important test for nebular models. However, our main result is to demonstrate that the ionizing stars of at least some UC H II regions are now open for business in the near-infrared.

2. DATA

We obtained spectra of G29.96–0.02 on the night of 1997 June 18 with the FSPEC spectrograph (Williams et al. 1993) on the Multiple Mirror Telescope. The seeing was about 1" FWHM, and the sky was clear. The spectrograph has a 172 × 32" slit and gave coverage from about 2.03 to 2.21 μm at a resolution of λ/Δλ ≈ 1000.

We obtained twelve 4 minute spectra of the ionizing star of G29.96–0.02 to give a total of 48 minutes of exposure. We interspersed observations of G29.96–0.02 with observations of the nearby bright A1 V star HR 7209.

Figure 1 shows near-infrared Brγ and K-band images of G29.96–0.02 taken from Watson et al. (1997). The images show clearly the ionizing star at the center of a bright arc of nebular emission. A fainter fan of emission extends away from the arc to the northeast. The spectrograph incorporates a slit viewing camera working in the H band, and so we were able to accurately position the slit and guide manually. We oriented the slit in elevation to simplify guiding, and as a result the slit rotated on the sky between position angles of 6° and 40°. We nodded the ionizing star along the slit.

We extracted the stellar spectrum in a synthetic aperture of 1/2" width centered on the ionizing star. This aperture matches both the image quality and the slit width. We also extracted spectra of the bright arc of the nebula to the south and west and the fainter, extended fan of the nebula to the north and east using apertures from 1/2 to 3/6 either side of the ionizing star.

We corrected for atmospheric absorption using the spectra of HR 7209. We removed the Brγ absorption by fitting and adding a Gaussian profile. While this will leave systematic errors of as much as 10% in this region, the Brγ line is of limited use, as it is heavily contaminated by nebular emission.

We used a blackbody with a temperature of 9970 K (Code et al. 1997) for the intrinsic continuum of HR 7209.

Our 12 individual spectra of G29.96–0.02 exhibited subtle ripples over scales of tens of pixels, the result, we think, of our relatively narrow synthetic aperture. To counter these ripples, we divided each spectrum by a fit to the continuum, then averaged the ratios (with 2 σ rejection) and the fits separately, and finally multiplied the average ratio by the average continuum fit to give an average spectrum. The distribution of the
Fig. 1.—(a) Brγ and (b) K-band images of the region around G29.96−0.02 from Watson et al. (1997). The axes mark arcseconds. The Brγ image has been scaled and subtracted from the K image to suppress nebular emission. Note the arc of bright nebular emission, the fan of fainter nebular emission extending to the northwest, and the ionizing star at the center of the arc.

Fig. 2.—(a) The nebular arc spectrum; (b) the ionizing star spectra. As described in § 2, spectrum A is not corrected for nebular emission, spectrum B is corrected to leave the Brγ and He i 2.0581 μm lines in neither emission nor absorption, and spectrum C is overcorrected.

individual spectra about the average spectrum implies a signal-to-noise ratio (S/N) of about 300, and examination of regions of the spectrum away from nebular, photospheric, and telluric features suggests that this S/N is indeed being achieved, at least in some places.

Figure 2a shows the nebular arc spectrum. The fan spectrum is similar, except that it has a lower S/N and the He i 2.1120 and 2.1132 μm lines are relatively weaker by about 10%. Figure 2b shows spectra of the ionizing star. The spectrum marked “A” is the total spectrum with no attempt to remove the nebular contamination. To create the spectrum marked “B,” we scaled and subtracted the arc nebular spectrum so that the Brγ and He i 2.0581 μm lines were in neither emission nor absorption. To create the spectrum marked “C,” we scaled and subtracted the arc nebular spectrum so that the Brγ and He i 2.0581 μm lines were unreasonably deep; the equivalent width of Brγ is about 33 Å in spectrum C, but in OB stars it is never deeper than about 10 Å (Hanson et al. 1996). Thus, the real spectrum of the ionizing star lies between spectra A and C and is probably closely approximated by spectrum B, other than near the strongest nebular lines. (We used the arc spectrum to correct for nebular emission, as it has a higher S/N than the fan spectrum. Thus, we will likely very slightly oversubtract the He i 2.1120 and 2.1132 μm lines.) It can be seen from the difference in the continuum fluxes between spectra A and C in Figure 2b that the veiling contribution of the nebular continuum is only about 10%−20%.

3. THE EFFECTIVE TEMPERATURE

The K-band spectral features of O stars are almost independent of luminosity class except for the Brγ and He i 2.0581 μm lines, which are obliterated in our stellar spectrum by nebular emission. Thus, we can determine the effective temperature of the star from its spectrum but not its luminosity class.

Figure 3 shows our normalized spectra along with spectra from the spectral atlas of Hanson et al. (1996) for O stars of type O3 V to O9.5 V (HD 93205, HD 168076, HD 93204, Cyg OB2 516, HD 168075, HD 467839, HD 101413, and HD 37468). The strong nebular contamination of the Brγ and He i lines means that we have no reliable information on these lines. Nevertheless, the characteristic spectral features of other ions are present in the spectrum of the ionizing star. First, the star clearly has strong C iv emission. Second, it has He ii absorption. Third, recalling that spectrum C is oversubtracted and noting the asymmetry of the stellar 2.11−2.12 μm feature compared with the nebular 2.11−2.12 μm feature, the star has N iii emission. The He ii absorption and N iii emission both imply that the star is kO8 or earlier, and the strong C iv emission limits the star to kO5−kO8 (cf. Table 6 of Hanson et al. 1996). (The “k” in this notation is an indication that these are K-band spectral types, not optical MK spectral types.) Normally, the strength of the N iii and C iv emission features would rule out spectral classes kO7 and kO8 because these features are weak in stars with metallicity near the solar value. However, the metallicity of G29.96−0.02, roughly twice that of the Sun, may enhance the strength of these features.
Spectral classes of kO5–kO8 correspond closely to MK spectral classes of O5–O8 (Hanson et al. 1996). This range corresponds to effective temperatures of about 46,000 to about 38,500 K (Vacco, Garmany, & Shull 1996).

We also note that the C iv and He ii lines seem broad with FWHM of about 500 km s⁻¹; we are planning to obtain spectra at higher resolution to investigate this further.

4. THE NATURE OF THE STAR

One of the objectives of this study was to check the conclusions of Watson et al. (1997), who noted that the star had an evolutionary age in excess of about 10⁶ yr in apparent contradiction to the estimated age of the UC H ii region of only 10⁵ yr. A zero-age main-sequence (ZAMS) binary could not satisfy their limits, and they rejected the possibility of a close triple system as too unlikely. They suggested that the best explanation was the idea of Bernasconi & Maeder (1996) that a massive star evolves as it accretes.

Figure 4 shows our limits on the effective temperature and the limits from Watson et al. (1997) on the effective temperature, luminosity, and distance. Also shown are evolutionary tracks and isochrones of the Z = 2 Z_⊙ models of Meynet et al. (1994). Our new limits are consistent with those of Watson et al. (1997). Taken together, the limits are consistent with a single or binary star with an apparent age of between about 1 and 2 × 10⁶ yr.

Might the apparent age of the UC H ii region be wrong? Long-lived UC H ii regions have recently been proposed by De Pree, Rodriguez, & Goss (1995) and García-Segura & Franco (1996). The basic idea is that the densities in molecular cores can be large enough to stall the expansion of the UC H ii region. We note, however, that G29.96−0.02 is not centered on the cloud core (see Fig. 6 of Watson et al. 1997) and appears to have entered a champagne flow phase (Lumsden & Hoare 1996). For the UC H ii to be of order 10⁶ yr old would require that its H ii region had been confined for most of this time but recently released. Both the confinement, given the location of the core, and the fine tuning of the release seem unlikely to us. We conclude that an age of order 10⁵ yr is likely to be correct.

Might the limits on the properties of the ionizing star be wrong? The limits of Watson et al. (1997) on the m_k and distance and our limits on the effective temperature seem to be very robust. The m_k depends only on directly observed quantities and the simple nebular physics of ionized hydrogen to determine A_k. Widening the distance limit of 5 kpc ≤ d ≤ 10 kpc to 4 or 11 kpc would imply unacceptably large random velocities of 30 km s⁻¹. Our effective temperature limit is derived by comparison of the observed spectrum of the ionizing star with well-calibrated spectral standards.

What about the limit on the effective temperature derived by Watson et al. (1997) from a consideration of the observed m bol and m_k? If, for the moment, we ignore this limit, we can satisfy the other limits in the small corner of the available parameter space occupied by binaries of O5 or O5.5 ZAMS stars at 5 kpc. (Earlier or later single stars or binaries are still forbidden by the robust limits on the effective temperature, m_k, and distance.) Such a binary would produce 20%–50% more than the 3 σ upper limit or 50%–100% more than the measured bolometric luminosity for the region; thus, a correspondingly large fraction must escape the UC H ii region. A close binary might also explain the broad photospheric lines seen in the spectrum. Whether this explanation is more acceptable than the one offered by Watson et al. (1997) is left to the judgment of the reader.
If we are to accept the idea that the ionizing star in G29.96−0.02 evolved significantly as it accreted, we must provide an explanation for why HD 93250 and O stars in M17 apparently have not (Hanson, Howarth, & Conti 1997). The time allowed for evolution to proceed during the accretion phase is inversely proportional to the mean accretion rate. It is possible, then, that accretion proceeded sufficiently quickly in M17 and HD 93205 that evolutionary effects are not noticeable, but slowly enough in G29.96−0.02 that they are. Models run at a number of accretion rates at metallicity values equal to and twice that of the Sun are needed to investigate this.

If the broad photospheric lines seen in our spectrum are the result of very rapid rotation, the von Zeipel effect will act to reduce the effective temperature of the equatorial regions. This could reconcile our luminosity and effective temperature with those of a single main-sequence star. However, we are doubtful that the effect can lower the temperature by the several thousand degrees required.

5. NEBULAR MODELS

Simpson et al. (1995) and Aferbach et al. (1997) have modeled the far-infrared emission lines of G29.96−0.02 and found best fits with ionizing stars that have effective temperatures that are cooler than our lower limit of 38,500 K. Similarly, Faison et al. (1997) have recently modeled the dust reemission of G29.96−0.02 and find a best fit with ionizing stars that have luminosities that are below our lower limit on the luminosity of the region. Clearly, satisfying our constraints on the stellar properties while correctly predicting the mid- and far-infrared emission will be an excellent test of models of the nebular emission. Success may require more complex models that pay attention to the geometry of G29.96−0.02, in particular its lack of spherical symmetry and wide range of ionization parameters.

In the meantime, we can use our limits to investigate the ionization in the nebula. The recombination rate of $3.15 \times 10^{-11} \text{ s}^{-1}$ at 5 kpc is a lower limit to the Lyman continuum photon flux of the ionizing star, as dust can absorb ionizing photons and, possibly, ionizing photons can escape from the nebula. We calculated this recombination rate from the intrinsic Brγ flux given by Watson et al. (1997) and the case B nebular models of Hummer & Storey (1984). If we use a fit to Figure 13 of Schaefer & de Koter (1997) to give $q_0(T)$ and $L = 4\pi R^2 \sigma T^4$ to give the Lyman continuum photon flux $Q_\alpha(L,T) = 4\pi R^2 q_\alpha$, then we find that the Lyman continuum flux exceeds the effective recombination rate by factors of about 1.5 (at O8) to about 4 (at O5). This suggests either that dust is a significant competitor for ionizing photons or that a significant fraction of the ionizing photons are escaping.

6. SUMMARY

We have successfully obtained a K-band classification spectrum of the ionizing star of the UC H II region G29.96−0.02. The lines of H I and He I are obliterated by nebular emission, but the spectrum shows C IV and N III emission and He II absorption. Using the classification scheme of Hanson et al. (1996), we can restrict the star to spectral classes O5–O8, which correspond to effective temperatures of 46,000–38,500 K.

When we combine our effective temperature limits with the absolute magnitude determined by Watson et al. (1997), we can place the star on the H-R diagram using only the relatively well-understood properties of the stellar photosphere and the ionized gas. Our limits are more robust than previous ones, which relied on a mixture of assumptions and models for the influence of the star on the surrounding ISM.

One direct result of this work is to provide a test case for models of the nebular line and dust emission; these must now satisfy the independent constraints on the effective temperature and luminosity of the ionizing star. In this context, the recently obtained Infrared Space Observatory SWS and LWS spectra of G29.96−0.02 will be a valuable resource. At moderate resolution ($\lambda/\Delta \lambda \sim 1000$), the strong nebular emission in UC H II regions obliterates the stellar H I and He II features, leaving us with just the C IV, N III, and He II features in the K band. The spectral types that can be determined from these features are quite rough: O3–O4 (N III emission and He II absorption but no C IV emission), O5–O6 (both N III and C IV emission and He II absorption), and O9 or later (none of these). Observations at high resolution ($\lambda/\Delta \lambda \sim 10000$) may be able to resolve the broad stellar lines from the narrow nebular lines but will be challenging.

This is the first time that the effective temperature of the ionizing star of a UC H II region has been determined directly. This technique may be feasible in other UC H II regions, although nebular veiling and higher extinction may be serious problems. This work is a further demonstration that K-band spectral classification, when combined with near-infrared imaging, is a uniquely powerful tool for the study of very young massive stars.

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