SPECTROSCOPIC CONFIRMATION OF THE DRAGONFISH ASSOCIATION: THE GALAXY’S MOST LUMINOUS OB ASSOCIATION

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Received 2011 October 28; accepted 2011 November 10; published 2011 November 23

ABSTRACT

Young OB associations with masses greater than $10^4\,M_\odot$ have been inferred to exist in the Galaxy but have largely evaded detection. Recently, a candidate OB association has been identified within the most luminous star-forming complex in the Galaxy, the Dragonfish Nebula. We identify 18 young, massive stars with near-infrared spectroscopy from a sample of 50 members within the candidate OB association, including 15 O-type and 3 luminous blue variables or Wolf–Rayet stars. This number matches the expected yield of massive stars from the candidate association, confirming its existence and ability to power the parent star-forming complex. These results demonstrate the existence of a $10^5\,M_\odot$ OB association, more powerful than any previously known in the Galaxy, comparable in mass only to Westerlund 1. Further, the results also validate the color selection method used to identify the association, adding credence to others discovered in the same way.

Key words: infrared: stars – open clusters and associations: individual (Dragonfish Association) – stars: formation – stars: massive

1. INTRODUCTION

The most luminous and powerful of a galaxy’s young stellar associations contain a significant fraction of its massive stars, and dominate all collective forms of energetic feedback into the galaxy’s large-scale wind, gaseous disk, and halo (McKee & Williams 1997; Dove et al. 2000). While the massive cluster populations of some other galaxies, such as M83, are well characterized (Chandar et al. 2010), only the closest couple kiloparsecs of the Milky Way have been probed in detail (Lada & Lada 2003). Across the Galactic plane, severe obscuration by dust and the high density of field stars have confounded searches for even the most luminous associations, leaving our knowledge of them incomplete. About 50 young OB associations with masses greater than $10^4\,M_\odot$ have been inferred to exist in the Galaxy (McKee & Williams 1997; Larsen 2009); however, they have largely evaded detection.

Our view of the Galactic population of H II regions is substantially more complete, thanks to radio surveys (Caswell & Haynes 1987) and subsequent follow-up studies. Of the identifiably coherent structures that emerge from such work, the most luminous is the so-called Dragonfish Nebula at $(l, b) = (298, -0.4)$ (Murray & Rahman 2010; Rahman & Murray 2010). Located on the far side of the Galaxy, 9.7 kpc through the Galactic disk, its morphology and radio velocities are indicative of an expanding bubble. Its H-ionizing luminosity of $10^{51.8}$ photons s$^{-1}$, if it originates from a coherent group of stars, requires the presence of the most luminous young stellar cluster or OB association in the Galaxy. The region’s distance and location in the Galactic plane imply a high degree of extinction, roughly $A_K \sim 1$ or $A_V \gtrsim 10$.

Using a near-infrared (NIR) color selection method, a candidate for the central powering source of the nebula was identified: the Dragonfish Association (Rahman et al. 2011). The association is composed of 406 ± 102 candidate O stars, consistent with the measured ionizing luminosity, making it one of the largest single OB associations or young clusters in the Galaxy ($M \sim 10^5\,M_\odot$). Notably, the candidate association is not projected toward one of the bright regions of H II and 8 μm emission in its vicinity, but within an evacuated shell surrounded by such emission. This suggests that the ionizing source has inflated a bubble of radius 69 pc within the Galactic disk. The overdensity of sources being indirect evidence, we seek direct spectroscopic confirmation that the overdensity consists of O stars, and that the field objects are K giants.

In this Letter, we confirm the existence of the Dragonfish Association through NIR spectroscopy of massive stars. In addition, we identify two candidate luminous blue variables (LBVs) and a Wolf–Rayet within the association. This verifies the presence of an OB association which, on the basis of source counts, is sufficiently luminous to power its host star-forming complex, giving it a total mass of $10^5\,M_\odot$ and making it the most luminous OB association in the Galaxy. The confirmation of the Dragonfish association validates the NIR color selection method as a way of identifying candidate clusters and associations in distant star-forming complexes.

2. OBSERVATIONS AND DATA REDUCTION

We conducted $H$- and $K$-band spectroscopy (1.52–2.4 μm) of 50 cluster sources projected toward the candidate association, and a control sample of four non-cluster sources, between 2011 March 16 and 20. We use the SOFI spectrograph at the 3.6 m ESO New Technology Telescope with the red grism and 0.6 slit providing a spectral resolving power of $R \sim 1000$. Both samples are limited to NIR colors consistent with extinguished O stars (or less extinguished K giants), and to $K$ magnitudes brighter than 12. The control sample is offset from the candidate association by 0.5 and should represent the interloper sources within the cluster sample. The total integration time is 60 minutes for each cluster source and 2 minutes for each non-cluster source, using the nod-and-shuffle technique. This provides minimum signal-to-noise ratios of $>250$ and $>50$, respectively. The data were reduced and analyzed with Python, using the numpy and scipy packages.

3. ANALYSIS AND RESULTS

3.1. Spectral Classification

From the NIR color identification method, the contaminating non-member population confused with the candidate association
is predominantly K giants with moderate extinction ($A_K \approx 0.3$; Rahman et al. 2011). Due to the high extinction, the intervening interstellar medium (ISM) will imprint absorption lines on the spectra as well, primarily from neutral metals (see Section 3.2). The NIR spectra of K giants are similarly riddled with neutral metal lines, causing difficulty in identifying O stars on this basis, at least at low spectral resolution (Rayner et al. 2009).

To discriminate between extinguished O stars and K giants, we concentrate on two absorption lines which are characteristics of massive young stars but absent or very weak in K giants. These are the 2.166 μm Br γ line and the 1.700 μm He i line, which is prominent in late-O stars. A number of weaker features, such as the 1.693 μm He ii line (present in early-O stars), 1.681 μm H i line, and the 2.188 μm He ii line, are also useful for identification.

In Table 1, we present the identified young massive stars: 15 O stars and 3 evolved massive stars. We present the spectra of a selection of these stars in Figure 1. We classify the NIR spectra of O stars with the Brackett series of hydrogen absorption lines and He i and He ii absorption lines. These features are weak, necessitating signal-to-noise ratios above 100 for detection (Hanson et al. 2005). We determine a subtype range and luminosity class with the aid of the weaker absorption lines and NIR photometry using the NIR extinction law from Nishiyama et al. (2009) and model photometry from Martins & Plez (2006). The magnitude differences between luminosity classes (from 0.2 to 1.0 mag in the K band) of the same spectral subtype ranges make it improbable for small differences in the extinction determination to change the luminosity class identification. We note that massive stars with weaker features, such as early-O stars lacking He i absorption or with Brackett γ absorption that has been filled in, may evade detection (Hanson et al. 2005). All except the most luminous stars (the WN9 and O4-6 stars) show strong Br γ absorption. The later stars all show He i absorption while the earlier stars show He ii absorption.

In addition to the 15 O stars, we identify one Wolf–Rayet star based on H i, He i, and He ii emission (Morris et al. 1996). Further, we find two candidate LBVs, based on numerous He i emission lines, and [Fe ii] emission in one case (Figure 2; Morris et al. 1996). These rare, exotic objects, transition stages of the most massive stars, are typically found in locations of recent star formation. Confirmation of the LBVs will require studies of their photometric variability.

### 3.2. Interstellar Features

The high signal-to-noise spectra of the massive stars presented in Figure 1 contain a number of features that are similar to features in the contaminating K-giant population. Riddled throughout the spectra are neutral metal lines, primarily from Mg, Al, Fe, and Si. These elements are common in the ISM and have been observed in absorption within the local 100 pc (Redfield & Linsky 2004). As such, these lines are expected to be imprinted on relatively featureless spectra when seen through a large column, as would be expected toward the association.

In addition to the metal absorption lines, strong CO vibrational absorption bands are visible in the spectra of all identified massive stars at 2.29, 2.32 ($ν = 2 → 0$), and 2.35 ($ν = 3 → 1$) μm. These are often detected as photospheric absorption features of K-giants (Rayner et al. 2009); however, they may be also imprinted on nearly featureless spectra of younger, more massive stars by interstellar absorption. The $ν = 2 → 0$ bands have been detected towards NGC 2024 IRS 2 with line widths $Δν = 1.4$ km s$^{-1}$ (Black & Willner 1984). The individual lines within each band are found to be saturated with total band equivalent widths of $~0.5$ Å (Lacy et al. 1994). Toward the Dragonfish region, there is CO emission detected between 10 km s$^{-1} < v_{lsr} < 30$ km s$^{-1}$ coincident with the Dragonfish association and its surrounding photon-dominated region (PDR; Grabelsky et al. 1988; Murray 2011). In the stacked cluster O-star spectra (see Section 3.3), the equivalent width of each of the CO bands is $~5$ Å, consistent with what is seen toward NGC 2024 when saturated over a larger range of velocities.

For the $ν = 3 → 1$ band to arise in the ISM, sufficient CO with excitation temperatures exceeding 1000 K must exist to populate the $ν = 1$ vibrational state. The PDR traced by polycyclic aromatic hydrocarbon emission in the region (Rahman & Murray 2010) is a likely site of such warm CO (Hollenbach & Tielens 1997). We note that CO $ν = 2 → 0$ and $ν = 3 → 1$ bands have been observed in absorption toward
massive stars in Cygnus OB2 classified by NIR and optical spectroscopy, at significantly lower dust extinctions than the Dragonfish’s (Comerón et al. 2008). Therefore, we conclude that CO absorption bands in the NIR spectra of the identified O stars are plausibly interstellar in origin, at least when the O stars are surrounded by an intensely illuminated PDR. However, this point deserves additional study.

3.3. Stacked Spectra Comparison

To investigate the weak NIR features in a more robust manner, we construct three groups of sources and examine the stacked spectra of each: the 15 cluster O stars, the 32 cluster sources not immediately identified as massive stars, and the 4 non-cluster field sources from our control sample. We present the stacked spectra in Figure 3. The primary spectral discriminators, Brγ and 1.700 μm HeI, are strong in the cluster O stars. Brγ is weaker but visible in the cluster contaminant population, and both lines are absent in the control non-cluster population. Further, weaker H1 absorption features at 1.514, 1.534, 1.544, 1.556, 1.570, and 1.681 μm, characteristic of massive stars rather than cool giants, are detected in the O star population and absent in the others. Conversely, the Ca and Fe feature at 2.26 μm, a characteristic feature in the spectra of cool stars, is strong in the non-cluster population, weak in the cluster contaminants, and absent in the O stars. In addition, differences between the three populations are visible with lines at 1.522 μm Mn, 1.529, 1.551, 1.573, and 1.697 μm Fe, and 2.207 μm Na/Sc, all of which are present in the non-cluster and contaminant populations, and either weak or absent in the O star population. These spectral differences confirm that the identification of the association O stars is robust.

3.4. Possible Runaway?

One of the identified O stars, Source 14 in Table 1, appears to be highly blueshifted in the 1.693 μm He II, 1.700 μm He I, 1.736 μm H I, and Brγ absorption lines. The blueshift of the lines corresponds to a radial velocity of 300 ± 50 km s⁻¹, as compared to the other O stars that show no significant Doppler shift. The velocity is much larger than can be explained by Galactic rotation. This indicates that the star is in a close binary system, or is a runaway O star either kicked out of the association or originating elsewhere. In our single-epoch spectrum, we find no indications of a companion star in the spectrum, such as splitting of spectral lines. If it is a runaway, it could have
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Figure 2. Spectra of the two candidate luminous blue variable candidates. The upper spectrum is star 9 and the lower is star 10 from Table 1. The error bars are indicated in gray. Characteristic spectral features are indicated. All spectral features are significantly stronger than those of the O-stars.

been produced by a binary–binary encounter or by the result of the supernova explosion of the primary of a massive binary (Gvaramadze et al. 2008). Similar massive runaways have been identified originating from Cygnus OB2 (Comerón & Pasquali 2007).

4. DISCUSSION AND SUMMARY

The spectroscopic identification of massive, young stars confirms the existence of a young OB association within the Dragonfish Nebula, but its share of the nebula’s ionization budget must be addressed statistically. Using the extracted candidate cluster properties from Rahman et al. (2011), we infer a membership probability of 35.5%, for an expected yield of 17.8 ± 3.4 members in the cluster sample. Indeed, 18 of our cluster sources are young, massive stars. This confirms that the Dragonfish Association is real, and not a chance sky overdensity of other stellar types (e.g., K-giants) coincident with the nebula or a spurious effect of intervening extinction. Further, this indicates that the NIR color selection method produces association membership probabilities consistent with the actual yield within the association.

From the point sources identified using the color selection method, assuming a minimum candidate spectral type of O9.5V (Martins et al. 2005) and using a standard stellar initial mass function (Kroupa 2001), the inferred total stellar mass of the association is ∼10^5 M☉ (Rahman et al. 2011). This is remarkably consistent with the estimated mass of the minimum stellar population required to power its central star-forming complex (Rahman & Murray 2010). This indicates that the Dragonfish Association dominates the ionization of its surrounding nebula. Further, the mass of this association is greater than other luminous associations in the Galaxy such as NGC 3603 (1.3 × 10^5 M☉), Trumpler 16 in the Carina Nebula (1.8 × 10^5 M☉), Cygnus OB2 (7.6 × 10^5 M☉), and the Arches (7.7 × 10^4 M☉; Weidner et al. 2010). It is similar to that of Westerlund 1 (10^5 M☉; Clark et al. 2005), however, the Dragonfish is significantly more luminous compared to Westerlund 1 based on its free–free luminosity (Westerlund 1 is not visible in the Wilkinson Microwave Anisotropy Probe free–free maps; Murray & Rahman 2010). This is consistent with the more evolved state of the massive stars in the latter. If the Dragonfish association is, in fact, the sole engine of the free–free emission in the complex, its output of 10^{31.8} H-ionizing photons per seconds is similar to that of R136, the dominant powering source of the most luminous HII region in the Local Group, 30 Doradus in the Large Magellanic Cloud (Parker & Garmany 1993; Evans et al. 2011).

The identification of O stars and evolved massive stars confirms the existence of the Dragonfish Association. The association is not embedded within a bright HII region, but rather a void of continuum and PAH emission surrounded by a shell, indicating that it is the central illuminating and inflating source of the Galaxy’s most luminous star-forming complex. As an extreme example of Milky Way star formation, the Dragonfish complex merits further study in a number of ways. Its large population of O stars, an estimated 13 with masses >100 M☉ (using the initial mass function from Kroupa 2001), makes it an ideal laboratory for investigations of environmental influences at the upper limit of stellar masses. With high-precision astrometry, its membership can be more firmly established and its internal kinematics can be probed. X-ray, radio, and γ-ray follow-up is warranted to identify colliding wind binaries and young stellar objects. Searches for IR excess
sources should reveal a population of new protostars triggered by its influence. Moreover, this influence should be sought in the dynamics of atomic and molecular gas in its environment.

Additional candidate associations have been identified toward star-forming complexes identified by Rahman & Murray (2010) using this method and will be characterized in a forthcoming paper. The confirmation of the Dragonfish Association adds significant credence to the hypothesis that color-selected clusters found toward the Galaxy’s most luminous star-forming complexes are in fact their driving stellar associations.

This work is based on observations collected at the European Southern Observatory, Chile (ESO 086.C-0502). We thank N. Murray, J. Graham, P. G. Martin, and R. Breton for comments and discussion. D-S.M. and C.D.M acknowledge support from the Natural Science and Engineering Research Council of Canada. We acknowledge the staff of the ESO La Silla Observatory. This paper is dedicated to the memory of Crystal Marie Brasseur.

**Facility:** NTT (SOFI)

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**Figure 3.** Stacked cluster O star (top, black line), cluster contaminant (middle, lighter, line), and non-cluster (bottom, lightest line) spectra. The error of the stacked spectra is at the 0.01% level and so is not indicated. Characteristic distinguishing spectral features are indicated for the O stars and K giants. The cluster contaminants likely include massive stars with features too weak to be identified on individual spectra.
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