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# A Near-Infrared Narrow-band Imaging Survey to Search for Massive Stars in Cl 1806-20

Michelle L. Edwards[1,2], Reba M. Bandyopadhyay[2], Stephen S. Eikenberry[2], Valerie J. Mikles[2,3], Dae-Sik Moon[4]

[1] Gemini Observatory, Southern Operations Center, La Serena, Chile
[2] Department of Astronomy, University of Florida, Gainesville, FL 32611
[3] Department of Physics and Astronomy, Louisiana State University, Baton Rouge, LA 70803
[4]Department of Astronomy and Astrophysics, University of Toronto, Toronto M5S3H8, Canada

**Abstract:** We survey the environment surrounding Cl 1806-20 using near-infrared narrow-band imaging to search for Br$\gamma$ features indicative of massive stars. Using this technique, we successfully detect previously identified massive stars in the cluster. While we detect no new emission line stars, establishing a firm upper limit on the number of Wolf Rayets and Luminous Blue Variables, we do find several candidate OB supergiants, which likely represent the bulk of the heretofore undiscovered massive star population. Finally, we present spectroscopic evidence for emission-line variability in LBV 1806-20. Our results highlight the advantages of using narrow-band imaging to search for massive stars.

## 1 Introduction

Discovered by Fuchs et al. (1999), Cl 1806-20 is home to a variety of rare objects, including a candidate Luminous Blue Variable (LBV 1806-20), multiple Wolf Rayets (WRs), a soft-gamma repeater (SGR 1806-20), and several OB supergiants (Fuchs et al. 1999; Eikenberry et al. 2004; Figer et al. 2005). At a distance of either $\sim$ 15 kpc (Corbel & Eikenberry 2004) or $\sim$ 9 kpc (Bibby et al. 2008), the cluster spans $\sim$ 40 arcseconds (2.9 pc or 1.7 pc respectively) on the sky. It is located in a heavily crowded region of the Galactic Plane with $A_V \sim 29$ mag (Corbel & Eikenberry 2004).

Although individual members of Cl 1806-20 have been identified on a case-by-case basis with spectroscopy, no systematic effort to take a census of the cluster's massive stellar population exists in the literature. To better constrain the membership of Cl 1806-20, we performed near-IR broad- and narrow-band imaging to search for candidate massive cluster stars. We focused on Br$\gamma$ emission indicative of stellar winds in massive stars (Hanson, Conti & Rieke 1996; Figer, McLean & Najarro 1997; Blum et al. 2001) and Br$\gamma$ absorption found in OB supergiants (Hanson et al. 1996).

For our study, we applied a novel technique. We constructed a color-color diagram using $J$, $K_s$, 2.16$\mu$m Br$\gamma$, and 2.27$\mu$m $K_{cont}$ photometry of sources in the vicinity of Cl 1806-20. We then identified stars with Br$\gamma$ emission or absorption at the known $J - K_s$ color of the cluster. This method helped us to visually distinguish emission-line stars in the cluster from both massive field stars in the line-of-sight and bright late-type stars in the foreground.

# 2 Observations

On 2005 August 26-27, we used the Wide Field Infrared Camera (WIRC, Wilson et al. 2003) on the Palomar 200" telescope to obtain $J$, $K_s$, 2.16$\mu$m Br$\gamma$, and 2.27$\mu$m $K_{cont}$ images of an 8.7$'$ $\times$ 8.7$'$ region around Cl 1806-20. The total exposure times were 13.5 minutes in Br$\gamma$ and $K_{cont}$, 90s in $K_s$-band and 48s in $J$-band.

We reduced the data with FATBOY, a Python based data pipeline developed at the University of Florida, and performed astrometry on these images using KOORDS in the KARMA software package. We then completed PSF photometry on our science frames with DAOPHOT II and ALLSTAR (Stetson 1987, 1992) and calibrated the $J$ and $K_s$ magnitudes for our sources with 2-MASS photometry. Using TOPCAT, the Tool for OPeration on Catalogues and Tables (Taylor 2005), we matched our data across all four bands.

We used the position of the first object discovered in the cluster, SGR 1806-20, with an RA = 18$^h$ 08$^m$ 39.32$^s$ and Dec = $-20°$ 24$'$ 39.5" (Kaplan et al. 2002) as the cluster centre. We then created a $J - K_s$ versus $Br\gamma - K_{cont}$ diagram of objects within a 2$'$ radius from this position (Figure 1). We calculated the 2-D projected distance between each field star and the cluster centre.

# 3 Estimating Equivalent Widths

The color-color diagram that we constructed from our photometry offers a useful visual tool for identifying unknown massive stars in the cluster (see Sect. 5). However, the narrow-band photometry also provides a quantitative measure of the strength of a star's Br$\gamma$ features, which we can compare to literature values. Since the 2.16$\mu$m Br$\gamma$ filter detects both stellar continuum and Br$\gamma$ emission or absorption, while the 2.27$\mu$m $K_{cont}$ filter detects only stellar continuum, non-zero values of $Br\gamma - K_{cont}$ are indicative of Br$\gamma$ features. Furthermore, the magnitude of the $Br\gamma - K_{cont}$ color difference is an estimate of the equivalent width (EW) of the line.

First, the instrumental $Br\gamma - K_{cont}$ values derived from our photometry must be calibrated to take into account differences in transmission and dust penetration by the two narrow-band filters. In Figure 1 there is a clear linear correlation between the $J - K_s$ and $Br\gamma - K_{cont}$ color of sources in the field. Using TOPCAT, we fit a line with slope (m) = 0.028 and y intercept (b) = -0.137 to the data points. For any given $J - K_s$ color, this line defines the expected value of $Br\gamma - K_{cont}$ for a star with neither Br$\gamma$ absorption nor emission; a narrow-band "zeropoint".

To find the calibrated $Br\gamma - K_{cont}$ value, $(Br\gamma - K_{cont})_{cal}$, of an individual star in our data set, we first solved the equation of the line using the star's $J - K_s$ value. This gave us the $Br\gamma - K_{cont}$ "zeropoint" for that particular object. We then subtracted this value from the photometrically derived $Br\gamma - K_{cont}$ color. Finally, using this equation:

$$W = (1 - 10^{-\frac{(Br\gamma - K_{cont})_{cal}}{2.5}})d\lambda \tag{1}$$

where W is the equivalent width of the line and $d\lambda$ is the band-pass of the filters ($\sim$ 220 Å), we estimated the equivalent width for the stars in our study.

# 4 Comparison to Previous Results

For the remainder of the paper, we adopt the Eikenberry et al. (2004) nomenclature when an object has more than one designation.

Three of the four WR stars, B, 10, and 22 appear in our catalog; Star 3 is the exception. The location of Star 3 in the densest, most confused region of the cluster prevented an accurate measure of its position or magnitude in one or more bands in our dataset. Star 22 has a reported Br$\gamma$ excess of -0.20 $\pm$ 0.01 with a $J - K_s$ error = 0.02. We find an EW $\sim -45 \pm 2$Å, in agreement with the EW $= -42 \pm 3$Å previously reported (Eikenberry et al. 2004). We measure a $J - K_s \sim 5$ mag for Star 22, consistent with earlier measurements of this source (LaVine, *private communication*).

In some cases obvious discrepancies between our EW estimates and previous data do exist, however upon examination we found that they were indicative of physical processes in the stars in question. For instance, our photometry shows a Br$\gamma$ absorption of 21 $\pm$ 2Å for Star B, seemingly at odds with its classification as a Wolf Rayet. However, comparison of our data with NIR spectra provided by Eikenberry et al. (2004) show that this result is consistent with the classification of Star B as a WCLd, a dust emission WR star with large NIR and MIR excess redward of 2.2$\mu$m. Since the $K_{cont}$ band used in our observations is located at 2.27$\mu$m, we expect the flux in this narrow-band to be greater than the flux in the Br$\gamma$ band. Thus, our apparent Br$\gamma$ "absorption" is in fact a documented $K_{cont}$ excess. We find a similar result for Star 10, also a WC9d. With a $J - K_s$ color $\sim$ 5.83 mag, this star is slightly redder than most stars in the cluster, likely indicative (as with Star B) of intrinsic reddening by circumstellar dust.

For many of the OB supergiants, we found that insufficient information in the literature prevented quantitative comparison. However, we note that it is easy to identify these sources as objects with Br$\gamma$ absorption upon visual inspection of our color-color diagram.

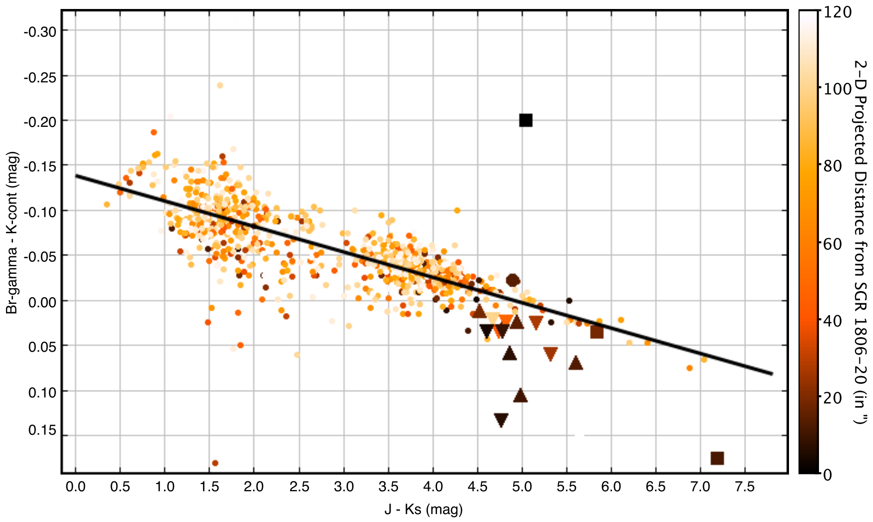


Figure 1: Color-color diagram of stars within a 2′ ($\sim$ 9 pc) radius of Cl 1806-20. OB supergiants are marked as triangles, WR stars as squares and the LBV as a circle. New OB supergiant candidates are marked as inverted triangles. The solid black line is the narrow-band zeropoint.

## 4.1 LBV 1806-20

Previously published spectra of LBV 1806-20 (Eikenberry et al. 2004, Figer, Najarro & Kudritzki 2004) reported a Br$\gamma$ EW $\sim -40$Å. However, with the method described above, we found a Br$\gamma$ EW $\sim -4 \pm 2$Å. To further investigate this result, we obtained spectra of LBV 1806-20 on 17 May 2004 and 2 July 2005 using the near-infrared spectrograph SpeX (Rayner et al. 2003) on the InfraRed Telescope Facility (IRTF). We reduced this data using standard SpeXTool procedure and produced flat-fielded, sky-subtracted, wavelength calibrated spectra for LBV 1806-20 for each of the two nights. Then, using Xcombspec (Cushing, Vacca & Rayner 2004) we combined the individual images of the

LBV to produce two, weighted-mean LBV spectra, one for 2004 and one for 2005. Finally, we divided the corresponding atmospheric standard from the program star, multiplied the LBV spectra by a 5600 K blackbody spectrum (the temperature of the standard), dereddened them using $A_v = 29$ mag and calculated the EW of all emission lines.

Our resulting K-band spectra appear in Figure 2. We find a Br$\gamma$ EW $\sim -7.9 \pm 0.4$Å in May 2004 and $-9.13 \pm 0.6$Å in July 2005 – substantially smaller than the EW found in the earlier observations by Eikenberry et al. (2004) and Figer et al. (2004), and much closer to the value derived from our narrow-band imaging – clearly indicating intrinsic variability in the Br$\gamma$ emission line.

Our broad-band photometry reinforces that LBV 1806-20 was undergoing a notable variation. We find $K_s = 8.56 \pm 0.03$ and $J = 13.45 \pm 0.04$ for LBV 1806-20, compared to $K = 8.89 \pm 0.06$ and $J = 13.93 \pm 0.08$ found by Eikenberry et al. (2004). Taking into account the errors and slight difference between the $K$- and $K_s$- bands, LBV 1806-20 is significantly brighter during our observations.

Recent findings by Rahoui, Chaty & Lagage (2009) in the mid-IR also confirm the variable nature of LBV 1806-20. Between October 2004 and September 2005, the authors observed a significant increase in the MIR flux. The flux then decreased from September 2005 - April 2006, returning to October 2004 levels. Without finer time-resolution, it is difficult to correlate changes in the MIR flux discovered by Rahoui et al. (2009) with the variability of the NIR spectroscopy and photometry presented in this study. However, we can say with certainty that between 2001 - 2006, LBV 1806-20 manifested the variability and instability expected from a star of this type. Extended monitoring of this object is necessary to better track future episodes.

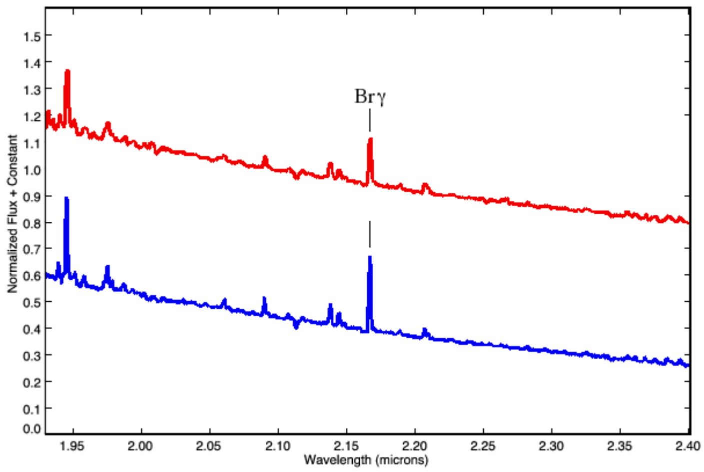


Figure 2: Spectra of LBV 1806-20 obtained with IRTF. The top spectrum was obtained in May 2004 and the bottom spectrum in July 2005. For clarity, each has been normalized by the last pixel and offset from each other by an arbitrary constant.

# 5 New Candidate Cluster Members

After confirming the efficacy of our method, we used the color-color diagram and our computed $Br\gamma - K_{cont}$ values to search for new massive stars in the cluster. We focused on objects with narrow-band emission or absorption that had the same $J - K_s$ color as known cluster members. Assuming $A_V = 29 \pm 2$ for Cl 1806-20, (Corbel & Eikenberry 2004) and $A_K = 0.112A_V$ and $A_J = 0.282A_V$

(Rieke & Lebofsky 1985) we calculated $A_K = 3.25 \pm 0.56$ and $A_J = 8.18 \pm 0.22$ for the cluster, yielding a $J - K_s = 4.93 \pm 0.34$ mag.

Using this criterion, we did not detect any previously unknown WR or LBV population in Cl 1806-20. This allows us to place a firm upper limit on the number of very massive stars in the cluster, which was the primary goal of this study. However, we did find a population of $\sim 10$ candidate OB supergiants that may represent the bulk of the heretofore undiscovered cluster population. We plan to perform follow-up spectroscopic observations of these targets.

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