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The Upper Main Sequence of the Open Cluster NGC 2169

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Abstract. A study of the B star population of the open cluster NGC 2169 through the combination of a variety of observational techniques raises interesting questions about the relationship between beta Cephei stars and Be stars, illustrating the necessity of spectroscopic observations to resolve ambiguities.

1. Introduction

This is a progress report on an ongoing study of NGC 2169, a nearby (~ 1 kpc) sparse open cluster selected to provide a test of techniques for investigating the occurrence of Be stars in relation to the evolutionary state of cluster B star populations. Its estimated age of 12 – 23 Myr (c.f. Perry, Lee, & Barnes 1978), falls within the range for which Fabregat & Torrejón (2000) found the highest fraction of Be stars.

Using a new single-object fiber spectrograph with the 1 m telescope at the University of Virginia Fan Mountain Observatory, medium resolution red spectra were acquired to the B9.5V limit for completeness and detection of weak Be stars not easily identified by Hα photometry. One B star was discovered to show an Hα line profile almost filled in by emission. It is a suspected β Cep variable with photometric evidence for Hα emission, but its inferred intrinsic properties and the presence of a sporadic component in its light variation suggest that it might instead be a classical Be star. (The term "classical Be star" was defined in the review paper by Porter & Rivinius (2003).) Further support for such an interpretation is presented here, based on a new analysis of existing visual and near infrared photometry.

This result reminds us that the area of overlap between Be stars, which seem to require some elusive mass loss mechanism acting in concert with their general rapid rotation, and β Cep stars, which can develop erratically variable circumstellar emission but include slow rotators, provides a valuable laboratory for searching out the missing element of the Be phenomenon.

2. A Visual Color-Magnitude Diagram

Figure 1 is a color-magnitude diagram based on fitting the *UBV* photoelectric photometry of Hoag et al. (1961) to the sequence of rotating B star models produced by Collins, Truax, & Cranmer (1991). The dashed lines represent dwarf and giant sequences for angular rotation velocities ranging from zero to "critical", with the combined effects of rotation and axial inclination indicated by "rotational displacement fans" branching from the nonrotating models for spectral types B1, B3, B5, B7, and B9. The zero age main sequence is from

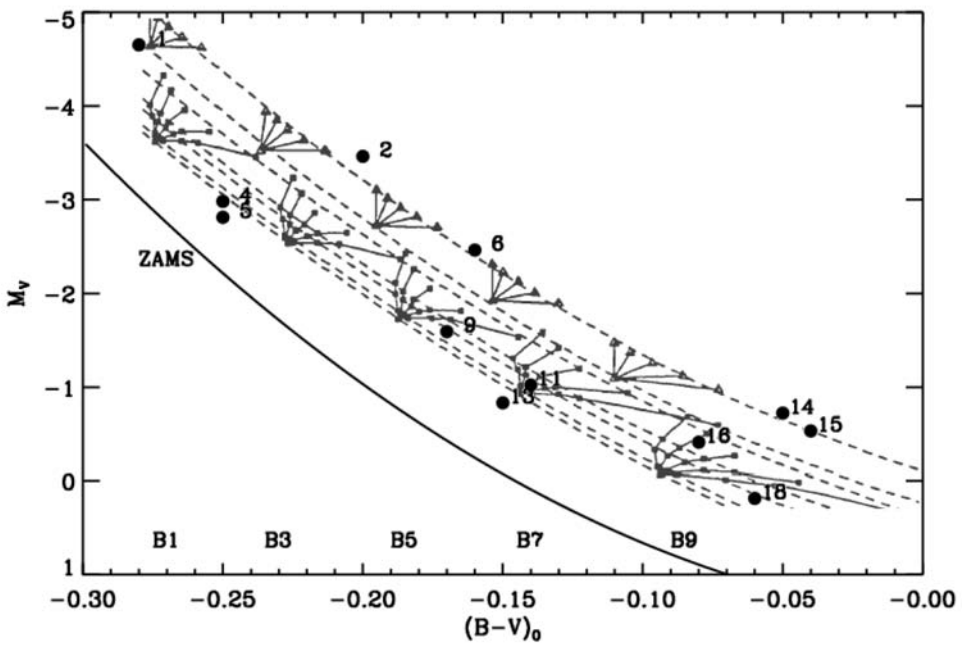

Figure 1. A color-magnitude diagram of NGC 2169 based on one possible fit of the *UBV* photometry of Hoag et al. (1961) to the sequence of rotating B star models by Collins et al. (1991).

Blaauw (1963). The upper main sequence of the cluster appears well-defined by the B stars labeled with Hoag catalog numbers 4, 5, 9, 11, 13, 16, and 18 if $E(B-V) = 0.19$ mag, $A_V = 0.59$ mag, and the corrected distance modulus $(V_0 - M_V) = 11.00$ mag, giving a distance of 1.58 kpc.

The suspected β Cep star NGC 2169-5=V 917 Ori discovered by Hill (1967) was the subject of intensive CCD photometry by Jerzykiewicz et al. (2003), who found a period of 0.267 d in V and used Strömgren photometric indices and a mean corrected distance modulus of 10.0 ± 0.3 mag derived from the literature to conclude that its temperature and luminosity were inconsistent with the explanation of the light variation as a β Cep pulsation.

The distance of 1.58 kpc is notably larger than those of previous studies because the main sequence has been matched to Collins' models, which are representative of field stars that have begun to leave the zero age main sequence. Even so, NGC 2169-5 (hereinafter referred to as H5) still lies near the lower edge of the β Cep instability strip (Stankov & Handler 2005; Sterken & Jerzykiewicz 1993), so the exact nature of this interesting stellar hybrid remains in question.

3. New Red Spectra of the B Star Population

The Fan Observatory Bench Optical Spectrograph (FOBOS) described in the paper by Crane et al. (2005) was used with the 1 m telescope at the University of Virginia Fan Mountain Observatory during 3 nights in 2004 February to obtain

medium resolution spectra ($\lambda\lambda$ 5800 – 6800 Å, R $\sim$ 3000, S/N $\sim$ 100) of 10 of the 13 B-type stars classified as members of NGC 2169 in the list compiled by Perry et al. (1978), and of 3 additional stars from the same list, two of which are suspected β Cep stars classified as nonmembers by those authors. Examples of the region around Hα λ6563 Å and He I λ6678 Å for a range of spectral subtypes from B1III (H1) to B9V (H16) are shown in Figure 2.

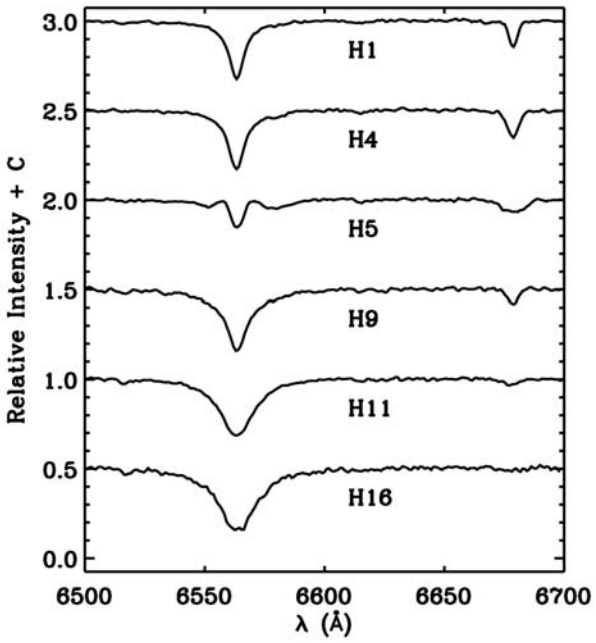

Figure 2. FOBOS red spectra of a representative sample of B stars in NGC 2169 showing the region of the Hα λ6563 Å and He I λ6678 Å lines.

The red spectra were intended primarily to improve the detection of Be stars with weak Hα emission which might be missed by narrow band photometry, but they served also as an experiment in using this region of the spectrum to distinguish the subtypes and luminosity classes of B stars.

4. The Emission Line Star H5: β Cep or Be?

Rectified Hα line profiles of the emission line star H5 and the normal B star H4 located at nearly the same position in the color-magnitude diagram are compared by overplotting in Figure 3. The line profile of H5 is consistent with the α index measured by Jerzykiewicz et al. (2003), which indicated a very small equivalent width in absorption. The Hα equivalent width for star H4 is 4.5 Å, in agreement with Collins' models for the spectral type B2V inferred from its position in the color-magnitude diagram.

If H5 is a β Cep star, time series spectra will show clearly a periodic radial velocity variation with the same period as the known light variation. A study

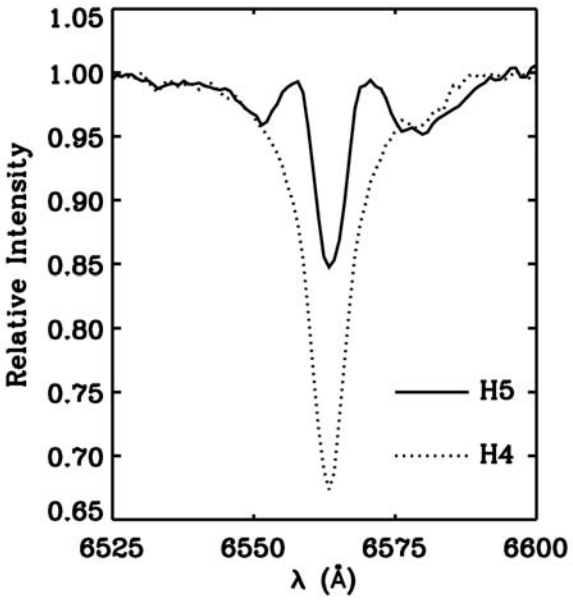

Figure 3. A comparison of the Hα line profiles of star H4, a normal B star, and star H5, which is either a β Cep star or a classical Be star.

of the Hα line profile variability would also be of great interest in light of the discovery by Hadrava & Harmanec (1996) that the prototype β Cep, which is a Be star with several documented strong emission-line phases and a magnetic Bp star as well, has shown double-peaked Hα emission with a radial velocity which varies in antiphase to the absorption radial velocity with the same period as the light variation. On the other hand, the absence of a periodic radial velocity variation in the time series spectra would prove that H5 is not a β Cep variable, but is instead a classical Be star.

5. 2MASS Near Infrared Photometry

Archived $JHK_{\rm S}$ photometry data from the 2MASS All-Sky Data Release[1] were used to construct the observational near infrared color-magnitude diagram shown in Figure 4. No attempt was made to correct for the effects of interstellar extinction. A smooth curve is drawn through Hoag stars 4, 9, 13, and 18 to delineate a main sequence which matches the visual color-magnitude diagram.

Given the range of values $0.0 \lesssim E(H-K)_{cs} \lesssim 0.3$ mag of the circumstellar component of the near infrared color excess and the positive correlation with emission line strength found by Howarth & Smith (2001) for a representative sample of Be stars, the color excess $E(H-K_{\rm S}) \sim 0.03$ mag of H5 suggested by

[1]See http://irsa.ipac.caltech.edu/.

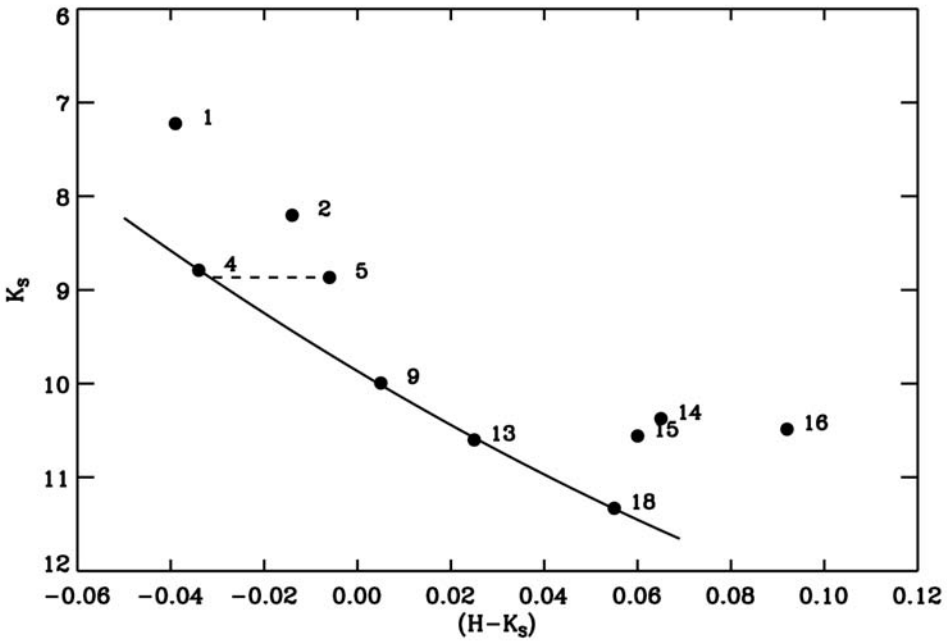

Figure 4. The 2MASS color-magnitude diagram shows an apparent near infrared color excess (dashed line) associated with star H5, the suspected Be star.

comparing its location relative to the main sequence in Figure 4 and Figure 1 would appear to be consistent with the presence of a weak Be-type circumstellar disk. (The source of the near infrared flux from the circumstellar disks of Be stars is generally thought to be free-free emission, since they show no evidence for dust.)

Thus the near infrared photometry data give some indication that H5 is a Be star. However, the JHK_S colors of emission-line β Cep stars, which are also Be stars by definition, must be compared carefully with those of classical Be stars before any distinction between the two types of star can be made on this basis.

6. Future Observing Plans

The red spectra presented here are valuable for detecting weak Hα emission in B stars, but the suspected presence of emission not only in Hα, but also in the He I lines, which are the only other strong features of B stars in this spectral region, severely limits their usefulness for spectral classification. Fortunately a new grating is now available for the FOBOS spectrograph, and it will be used to take blue spectra of the B star population of NGC 2169 over the classical "classification region" of the MK system ($\lambda\lambda$ 3900 – 4900 Å). This will give more accurate spectral types which will greatly improve the determination of the cluster distance and the analysis of cluster membership.

A new near infrared camera designed to work in the JHK_S passbands is now in operation on the 0.8 m telescope at Fan Mountain Observatory. It is equipped with a pair of Wollaston prisms mounted near the cold collimated pupil for polarimetry of point sources and uncrowded star fields. Observations with this instrument will yield polarization maps of open clusters such as NGC 2169 showing details of the distribution of foreground interstellar dust and providing the means to detect intrinsic polarization of cluster members, including Be stars. Photometric data may also be extracted from these measurements and used to identify stars with circumstellar matter, and the three passbands should make it possible to distinguish between dust and gas envelopes by their color indices.

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Discussion

H. Henrichs: Star #5 looks like a fast rotator as judged from the He I lines in your plot. It would be not uncommon to find a rapidly rotating β Cep star.

D. McDavid: I see what you mean, but I am reluctant to judge the rotation velocity of a Be star from the He I λ6678 Å line profile because it may not be entirely photospheric and it might be contaminated by emission. When I have blue spectra of this star in addition to the red spectra, I will show you a tabulation of FWHM measurements for the He I and Mg II lines.