A FUSE Survey of Be Stars in Galactic Clusters

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Abstract

We propose a survey of Be stars that reside in galactic clusters to determine the abundances of carbon and nitrogen in their photospheres. During the past two decades there has been a consensus that the rotation rates in Be stars are rapid but far short of their critical values ($0.50 \lesssim V/V_{cr} \lesssim 0.85$). But recently there has been a renewed interest in the possibility that Be stars are critical rotators (Townsend, Owocki, & Howarth 2004). Abundance studies can provide a test for the latter hypothesis, as stellar evolution modeling by Meynet & Maeder (2000) has predicted a significant enhancement in the photospheric N abundances in very rapidly rotating OB stars due to mixing of CNO-processed material from their interiors. The FUV is the best spectral region for determining CN abundances in Be stars as the strongest lines of C II, III and N II, III fall in this region and the flux contribution from the disk is not important. The survey will include Be stars in h & χ Per, a galactic cluster that contains a large fraction of Be stars, NGC 3766, and NGC 4755, and provide an independent test of the critical rotation hypothesis and contemporary stellar evolution models that include stellar rotation.

Investigator List

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Scientific Justification

1. Introduction

The cause(s) for the mass loss in Be stars remains one of the longest standing unsolved problems in stellar astrophysics. The first Be star (γ Cas) was discovered by A. Secchi in 1867 and both long-term and short-term variability in Be emission line envelopes were known to exist before 1900. A long-lived model proposed by Struve (1931) explained the apparent mass loss to a circumstellar disk as a result of critical rotation, however idea fell out of favor in the early 1980s primarily because of a statistical study by Balona (1975), new spacecraft observations that revealed variability in structured wind lines and a strong FUV flux level, the discovery of nonradial pulsations and some multiple periods, and the general consensus that the dramatic mass loss events and spectral variability typically seen in Be stars cannot be explained by fast rotation alone (cf. Porter & Rivinius 2003 for a review of contemporary research). Recently there has been a renewed interest in the possibility that Be stars are critical rotators (Townsend, Owocki, & Howarth 2004). The latter authors point out that projected rotational velocities determined from line widths would be underestimated if the star's photosphere is substantially gravity-darkened due to very rapid rotation. Although this is not an entirely new idea, it has rewinded one that critical rotation might not be entirely ruled out from the analysis of line profile data alone. Challenges have been swift and two new papers critically examining the effect of gravity darkening on B star parameters (Frémat at al. 2005) and a new statistical investigation (Cranmer 2005) again bring the expected maximum V/V_{cr} for Be stars back to the previous consensus value of $\lesssim$0.90.

Abundance studies can provide a good *independent* test for critical rotation in Be stars. Stellar evolution models by Meynet & Maeder (2000) predict a significant enhancement in the photospheric N abundances in very rapidly rotating OB stars due to mixing of CNO-processed material from their interiors. The shallow, rotationally-broadened lines in most Be stars, however, render abundance analyzes extremely difficult from optical spectra. Spectral lines in the optical region can also be further weakened and falsified by continuum and line emission from the disk. In contrast, the FUV region contains a number of strong lines of C II, C III, N II, and N III that are prominent even if the star's v sin i is large. An analysis of *Copernicus* FUV spectra of the moderately-rotating (v sin i ∼165 km s^{-1}) Be stars μ Cen and υ Cyg suggested a solar nitrogen abundance, but a possible underabundance of carbon (Peters 1979). Underabundances of many light elements were found in an earlier analysis of the sharp-lined Be star HR 2825 (Kodaira & Scholz 1970) from optical data alone but the line strengths may have appeared weaker due to envelope emission.

TABLE 1 - PROGRAM STARS†

Star	Cluster	V	Sp Type	v sin i (km s^{-1})
BD +56°548	h & χ Per	9.65	B1.5 IIIe	150
BD +56°559	h & χ Per	9.96	B1 IIIe	150
HD 14422	h & χ Per	9.39	B0.5 IIIe	100
BD +56°573	h & χ Per	9.66	B2 IIIe	300
BD +56°582	h & χ Per	9.72	B1 IIIe	150
CPD -60°3129	NGC 3766	9.40	B2.5 Ve	150
CPD -60°3157	NGC 3766	8.54	B3 Ve	170
CPD -59°4558	NGC 4755	9.38	B1 Ve	200
CPD -59°4553	NGC 4755	9.55	B1.5 Ve	165

† Spectral types and projected rotational velocities from Slettebak (1985)

2. Scientific Objectives, Why FUSE Observations are Needed, and Significance to Astronomy

To look for the possible presence of rotationally-enhanced nitrogen in the photospheres of Be stars, we propose a *FUSE* survey of Be stars in galactic clusters. Since the age of the cluster is known, we can place a reasonable limit on just how massive an individual star can be, and how much gravity-darkening is possible (a B star rotating at a critical velocity mimics a star of lower mass, cf. Townsend et al. 2005 and references therein). The program stars, listed in Table 1, were selected from lists in Slettebak (1985) using the criteria that the cluster falls in the part of the sky observable with *FUSE* in Cycle 7, the observed or predicted flux in the *FUSE* spectral region is less than the bright limit but not so faint that the exposure time would be more than 30 ks, and that the value of v sin $i \simeq 200$ km s^{-1}. We included one star (BD +56°573, that resembles the bright Be star χ Oph) for which the v sin i is listed as 300 km s^{-1} because it displays extremely strong Balmer emission that implies its mass loss rate is currently rather large. This proposal is a galactic counterpart of another that we submitted in Cycle 7 (05-FUSE7-0047) to determine the CN abundances in NGC330-B12, a sharp-lined B2IIIe star in the SMC.

Unlike the optical region, the FUV is rich in strong lines of carbon and nitrogen. Prominent in the *FUSE* spectral region are the C II 1010, 1036, and 1066Å doublets, the C III 977Å resonance line and 1176Å multiplet, the N II 1085Å multiplet, and the N III 991Å resonance multiplet and 1184Å doublet. We propose an analysis of these lines, similar to our study of the sharp-lined B0.5V field star AV 304 in the SMC (Peters & Adelman 2005a,b). In Fig. 1a we show our synthesis of the 1180Å region that contains strong lines from C III and N III. Note the close matching of the multiplet structure in C III 1176Å and the implied

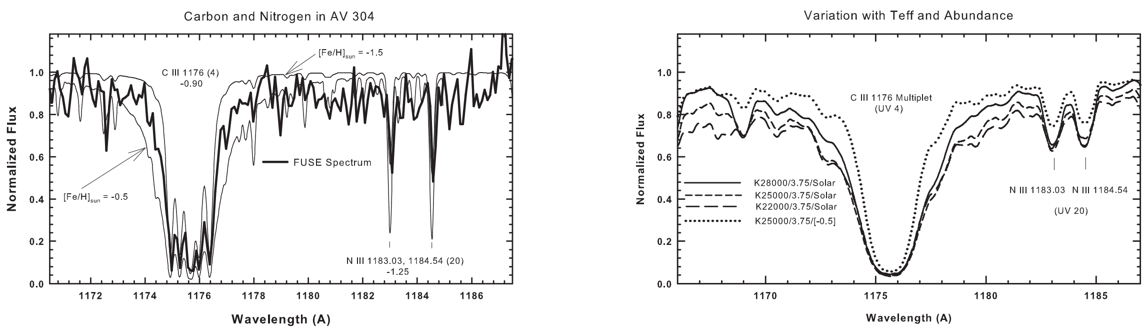

Figure 1: a. *Left panel*- The *FUSE* spectrum of AV 304 (B0.5V), a sharp-lined field star in the SMC, in the region containing C III 1176Å (UV 4) and the 1184Å, doublet of N III compared with synthetic spectra computed with SYNTHE (Kurucz 1993a). Note the very low N abundance in AV 304. b. *Right panel* - SYNTHE calculations for models with T_{eff}=25000-28000 K, log g=3.75 for solar abundances and a v sin i = 125 km s^{-1}. A spectrum for a star with abundances that are lower by 0.5 dex is shown for comparison. Note that even with a moderate rotational velocity the C III and N III features are quite prominent.

low abundances, especially for nitrogen in which we obtain $[N/H]_{\odot}$=-1.25. In Fig. 1b we show line profile calculations for the 1180Å region for a range of effective temperature that includes stars in the range B0.5-B2. All calculations were carried through with a log g of 3.75 and v sin i of 125 km s^{-1}that are typical for the program stars listed in Table 1. Even with a moderate rotational velocity the C III and N III features are quite prominent, unlike optical features. The strengths of both carbon and nitrogen features depend primarily on abundance.

The survey includes Be stars in h & χ Per, a galactic cluster that contains a large fraction of Be stars, NGC 3766, and NGC 4755. In a recent study of rotation in h & χ Per, Strom et al. (2005) concluded that the mean v sin i for the clusters is more than twice the average for field B stars. Since the very large angular momentum in the cluster would have favored the formation of critically-rotating objects, this is an excellent location to look for rotationally-enhanced N abundances.

This project provides a unique opportunity to test the widely debated hypothesis that Be stars rotate at/near their critical velocities. In addition to abundances of C and N, the *FUSE* spectral region contains strong lines of Si III, Si IV, S IV, and the resonance multiplet of Fe III at 1130Å. These lines will also be analyzed to determine the silicon, sulfur, and iron abundances in Be stars. In a series of recent papers Maeder and Menyet have investigated how rotation affects stellar evolution, mass loss, and alteration of surface abundances (Maeder & Menyet 2000, 2003, and references therein). If the star rotates near its critical velocity the effects can be large. This project will not only provide an independent test of the critical rotation hypothesis but also of contemporary stellar evolution models that include stellar rotation.

Feasibility and Safety Considerations

All program stars are located in the far northern/southern parts of the sky that will be accessible in *FUSE* Cycle 7. The FUV flux at 1170 Å is well-known for half of the program stars since they were observed with the *IUE* LORES camera. For the other objects, we used the *FUSE* Blackbody UV Flux Calculator, Version 2.0, that is available through the *FUSE* website. In the observing summary at the end of this proposal, we list the flux accuracy as high if *IUE* observations exist in the MAST archive and medium if the blackbody tool was employed.

To estimate the desired S/N, we have relied on our experience, since we have already carried through spectrum synthesis abundance analyses of several B stars using *FUSE* data (e.g. Peters & Adelman 2005a,b). An example is seen in Fig. 1a. In order to measure weak lines, we must be able to detect features of about 20 mÅ , which requires a S/N of about 15 over the spectral region of study. We used the *FUSE* on-line Exposure Time Tool, Version 7.0, to determine the exposure times necessary to achieve a S/N of 15 for each of the program stars using either the observed or computed flux at 1150 Å .

Description of the Observations

The observations will be carried through in the *FUSE* survey mode. We request one observation of each program star for a duration that is necessary to achieve a S/N$\sim$15 in either LiF2 channel or the final coadded spectrum. The LWRS aperture is suitable in all cases, as the objects are isolated from their neighbors.

Additional Information

The data will be analyzed using the technique of spectrum synthesis and LTE & NLTE codes. In the LTE study (cf. Adelman et al. 2001), we will use the code SYNTHE (Kurucz, 1993a) and line-blanketed model atmospheres computed from ATLAS9 (Kurucz 1993b) that contain the opacity effects of microturbulence in their construction. The NLTE study will be carried through using the program TLUSTY/SYNSPEC (Hubeny 1988, Hubeny & Lanz 1992). The Kurucz code is currently operational at The Citadel on Adelman's workstation and Adelman plans to install the Hubeny code on his G4 Macintosh or a PC/LINUX machine in the near future. Adelman and Peters will undertake the abundance analyses.

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Previous FUSE Observing Programs

A155 - "Observation of the Accretion-Driven Bipolar Flows in the Interacting Binaries TT Hya and V356 Sgr", G. J. Peters, P.I., R. S. Polidan, D. E. Lynch, co-Is. Results were presented at the 197th AAS meeting in San Diego in 2001 January (Polidan, R. S., Peters, G. J., & D. E. Lynch 2000, BAAS, 32, 1046) and at the 198th AAS meeting in Pasadena, CA in 2001 June (Peters, G. J., Polidan, R. S., & Lynch, D. E. 2001, BAAS, 33, 848). Project continued in FUSE Cycle 3 (C157).

C157 - "A Study of the High Temperature Polar Plasma in B-Type Interacting Binaries", G. J. Peters, P.I., R. S. Polidan & I. Hubeny, co-Is, continuation of A155. Results were presented in talks at the IAU General Assembly in Sydney, Australia (JD09) and at the 2004 FUSE conference in Victoria, BC "Astrophysics in the Far Ultraviolet". Publication: "Eclipse mapping of the Hot Circumstellar Plasma in Algols", Peters, G. J., & Polidan, R. S. 2004, Astr. Nach., 325, 225. A follow-up manuscript is currently in preparation.

C158 - "Heavy Element Abundances in Two B0-B0.5 Main Sequence Stars in the Small Magellanic Cloud", G. J. Peters, P.I. & S. J. Adelman, co-I. Results were presented at the 201st AAS Meeting in Seattle in 2003 January (Peters, G. J., & Adelman, S. J. 2002, BAAS, 34, 1285) and in a poster presentation at the 2004 FUSE conference. Publication: "The Abundances of the Fe Group Elements in AV 304, a Main-Sequence B0.5 Star in the Small Magellanic Cloud", Peters, G. J.,& Adelman, S. J., submitted to ApJ in 2005 September. Preprint to be available on ASTRO-PH.

D138 - "The Abundances of the Iron Group Elements in Early B Stars in the Magellanic Clouds", G. J. Peters, P.I. & S. J. Adelman, co-I. Our abundance analysis of 5 stars is in an advanced stage. Model spectra have been computed and we are now refining the abundances. We plan to present a poster containing results at the 207th AAS Meeting in Washington, DC in 2006 January.

E949 - "A FUSE Survey of Algol-Type Interacting Binary Systems", G. J. Peters, P.I., T. Ake, B-G Andersson, R. S. Polidan, R. Sankrit, co-Is. Survey program currently in progress. Early results were presented at the 205th AAS meeting in San Diego in 2005 January (Peters, G.J., Andersson, B.-G., Ake, T.B., & Sankrit, R. 2004, BAAS, 36, 1527). Publication: "it FUSE Observations of an Accretion Hot Spot and Associated *Splash* Plasma in the Direct Impact Algol Binary U Cephei", Peters, G. J., Andersson, B.-G., Ake, T. B., & Sankrit, R., to be submitted to ApJL in 2005 September-October. We will post a preprint on ASTRO-PH.

Vita

GERALDINE J. PETERS (Ph.D., Astronomy, UCLA, 1974; M.A., Astronomy, UCLA, 1966, B.S., Long Beach State Univ., Physics, 1965) has been involved with the analysis and interpretation of spacecraft data on early type stars since 1974 (missions include *Copernicus, IUE, HST, Voyager UVS, EUVE, ORFEUS-SPAS 2, FUSE, ROSAT, and SAS-3, Uhuru, Pioneer 10/11*). Her research specializations include the CS environment about B stars and interacting binaries with B or A primaries and non-degenerate secondaries and studies of fundamental properties of B stars. She is currently a Research Professor at the University of Southern California (Space Sciences Center, Dept. of Physics & Astronomy). Other positions: Res. Scientist, USC, 1985–2001; Visiting Prof., Pomona College, 1992–93; Visiting Assoc. Prof., UCLA (Astr. Dept.), 1986; Visiting Faculty, UCLA (Astr. Dept.), 1983–85; Adj. Asst. Prof., USC (Astr. Dept.), 1978–85; Physicist, Center for Astrophysics, 1976–78; Lecturer, Res. Assoc., Res./Teaching Asst., UCLA (Astr. Dept.), 1972–76.
Selected Publications
1. "The Development and Behavior of an Active Region On/Near the Photosphere of the B2e Star μ Centauri", Peters, G. J. 1998, ApJ, 502, L59
2. "The Algol-Type Binaries", Peters, G. J. 2001, in The Influence of Binaries on Stellar Population Studies", ed. D. Vanbeveren (Dordrecht: Kluwer), 79 (Invited Review)
3. "HR 2142, Thirty Years After it was Hypothesized to be an Interacting Binary", Peters, G. J. 2001, Publ.Astron.Inst.Acad.Sci.Czech Republic, No. 89, 30
4. "Eclipse Mapping of the Hot Circumstellar Plasma in Algol Binaries", Peters, G. J., & Polidan, R. S. 2004, Astr. Nach., 325, 225
5. "The Abundances of the Fe Group Elements in the Early B Star AV 304 in the Small Magellanic Cloud", Peters, G. J., & Adelman, S. J. 2005, in Astrophysics in the FUV, Five Years of Discovery with FUSE, ed. G. Sonneborn, H. W. Moos, & B.-G. Andersson (San Francisco, ASP) , in press

SAUL J. ADELMAN (Ph.D., Astronomy, Caltech, 1972, B.S., Physics, Univ. Maryland, 1966) has been a Professor of Physics at The Citadel since 1989. Other positions include Assoc./Asst. Prof., The Citadel (1978-89), Asst. Prof., Boston Univ. (1974-78), NAS/NRC Postdoc, NASA/GSFC (1972-74)
Selected Publications:
1."On the Relationship Between the Mercury-Manganese Stars and the Metallic-lined stars", Adelman, S. J., Adelman, A. S., & Pintado, O. I. 2003, A&A, 397, 267
2. "Heavy Element Abundances in Late B and Early A Stars: I. Coadded IUE Spectra of HgMn Stars" Adelman, S. J., Proffitt, et al. 2004, ApJS, 155, 179

DAVID A. MCDAVID (Ph.D., Univ. Amsterdam, 2001; M.A., Univ. Virginia, 1977; B.S., Stanford Univ., 1972) has been a Research Associate at the University of Virginia since 2002. Other positions include Teaching Associate, Univ. of Texas at San Antonio, 1977-1992.
Selected Publications:
1. " Multicolor Polarimetry of Selected Be Stars: 1990–93", McDavid, D. 1994, PASP, 106, 949
2. "A Useful Approximation for Computing the Continuum Polarization of Be Stars", McDavid, D. 2001, ApJ, 553, 1027

Observing Summary:

Object name IntTime	RA Dec	V E(B-V)	Spec Spec Src	λ_{ref} $Flux_{\lambda ref}$	FWHM $SB_{\lambda ref}$	Aperture FluxAcc	S/N Resln Channel	Special Req
BD+56D548 20000 s	2:20:39.03 +57:18:43.5	9.65 0.8	B1.5IIIe PC	1150 2.0e-13		LWRS HIGH	15 0.05Å LIF2	
BD+56D559 26000 s	2:21:18.07 +57:18:22.1	9.96 0.8	B1IIIe PC	1150 1.0e-13		LWRS HIGH	15 0.05Å TOTAL	
HD14422 20000 s	2:21:50.81 +57:23:11.6	9.39 0.8	B1.5IIIe PC	1150 2.0e-13		LWRS HIGH	15 0.05Å LIF2	
BD+56D573 7000 s	2:22:06.36 +57:05:25.1	9.66 0.8	B2IIIe PC	1150 6.0e-13		LWRS HIGH	15 0.05Å LIF2	
BD+56D582 23000 s	2:22:22.75 +57:17:05.0	9.72 0.8	B1IIIe PC	1150 7.0e-14		LWRS MED	15 0.05Å TOTAL	
CPD-60D3129 7000 s	11:36:12.38 -61:32:45.2	9.40 0.2	B2.5Ve PC	1150 6.0e-13		LWRS MED	15 0.05Å LIF2	
CPD-60D3157 5000 s	11:36:31.57 -61:34:25.5	8.54 0.2	B3Ve PC	1150 8.0e-13		LWRS MED	15 0.05Å LIF2	
CPD-59D4553 5000 s	12:53:48.00 -60:22:00.0	9.55 0.4	B1.5Ve PC	1150 5.0e-13		LWRS MED	15 0.05Å TOTAL	
CPD-59D4558 5000 s	12:53:52.03 -60:22:15.4	9.38 0.4	B1Ve PC	1150 1.2e-12		LWRS MED	15 0.05Å LIF	