Blue Hook Stars in Globular Clusters

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ABSTRACT
Blue hook (BHk) stars are a rare class of horizontal branch stars that so far have been found in only very few Galactic globular clusters (GCs). The dominant mechanism for producing these objects is currently still unclear. In order to test if the presence of BHk populations in a given GC is linked to specific physical or structural cluster properties, we have constructed a parent sample of GCs for which existing data is sufficient to establish the presence or absence of BHk populations with confidence. We then compare the properties of those clusters in our parent sample that do contain a BHk population to those that do not. We find that there is only one compelling difference between BHk and non-BHk clusters: all known BHk clusters are unusually massive. However, we also find that the BHk clusters are consistent with being uniformly distributed within the cumulative mass distribution of the parent sample. Thus, while it is attractive to suggest there is a lower mass cut-off for clusters capable of forming BHk stars, the data do not require this. Instead, the apparent preference for massive clusters could still be a purely statistical effect: intrinsically rare objects can only be found by searching a sufficiently large number of stars.

Key words: globular clusters: general — stars: horizontal branch

1 INTRODUCTION
The horizontal branch (HB) in globular clusters (GCs) represents the Helium core burning phase of stellar evolution. HB morphology varies from cluster to cluster; some clusters show a red HB (RHB), others a blue HB (BHB), and some even a bimodal HB with both a RHB and BHB. Some BHBs exhibit a long, vertically extended tail in optical colour-magnitude diagrams (CMDs), which is formed by particularly hot objects. BHB stars hotter than $T_{\text{eff}} \approx 20000$ K are usually referred to as extreme HB (EHB) stars and are thought to have undergone severe mass loss during their RGB phase (e.g. Momany et al. 2004). They evolve into AGB manqué stars or post-early AGB stars, but do not return to the AGB (e.g. Dorman et al. 1993). In a few GCs, the hottest – and optically faintest – end of the EHB at $T_{\text{eff}} > 31500$ K is populated by a peculiar class of objects which was first detected in ω Cen and NGC 2808. They form a blue hook (BHk) at the hot end of the HB in far-UV (FUV) CMDs and were consequently called “blue hook stars” (Whitney et al. 1998, D’Cruz et al. 2000, Brown et al. 2001).

The physical mechanism that produces BHk populations is still uncertain. At least two scenarios have been proposed.

In the late He flasher scenario these stars are explained as a consequence of extreme mass-loss during the RGB phase and late He-flashing while descending the white dwarf (WD) cooling sequence (e.g. Dorman et al. 2001). Due to the thin residual H-envelope, He is mixed into the envelope and H is mixed into the core during the late He-flash. As a result, the stars are hotter and UV-fainter than canonical EHB stars.

In the He self-enrichment scenario the EHB and BHk stars are produced via the normal evolution of He-enhanced sub-populations in GCs. For example, Lee et al. (2005) were able to explain the peculiar HB morphology and the presence of BHk stars in NGC 2808 and ω Cen with several He-enhanced sub-populations within these clusters.

By contrast, in the He self-enrichment scenario the EHB and BHk stars are produced via the normal evolution of He-enhanced sub-populations in GCs. For example, Lee et al. (2005) were able to explain the peculiar HB morphology and the presence of BHk stars in NGC 2808 and ω Cen with several He-enhanced sub-populations within these clusters. These sub-populations might have formed from the ejecta of intermediate-mass AGB stars of the first generation of stars (see also D’Antona et al. 2005). For the same age and metallicity, He-enhanced HB stars have smaller masses than

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normal HB stars, resulting in bluer ZAHB locations (Lee et al. 1994). They are also brighter in the FUV, but this effect is reversed for very hot He-enriched HB stars with $T_{\text{eff}} > 19000$ K. Lee et al. (2005) also predicted a narrow split in NGC 2808’s main sequence (MS), which was indeed found by D’Antona et al. (2005) and Piotto et al. (2007).

One way to make progress in understanding the nature of BHk stars and their progenitors is to test if the presence of BHk populations is associated with particular cluster properties. For example, if He-enriched populations are needed to produce BHk stars, these stars would then only be expected in GCs that exceed some critical mass threshold needed to keep the stellar ejecta from the first generation of stars within the cluster potential. Alternatively, if He enrichment is not important in the production of BHk stars, the mass loss required by the late-He flash could be due to dynamical processes, such as binary interactions. In this case, one might expect that only clusters with high encounter rates host BHk populations.

In order to address these questions, we have constructed a sample of GCs in which the presence or absence of BHk populations can be established with a high degree of confidence. More specifically, since BHk stars can (only) be easily recognized in UV CMDs, we restrict our sample to GCs for which sufficiently deep (space-based) FUV or near-UV (NUV) observations are available. Using this sample, we are able to search for any correlations between the existence of BHk populations and the properties of their host clusters (e.g., metallicity, mass, relaxation times etc.). Our results do confirm suggestions in the literature that BHk stars are preferentially found in massive clusters (e.g. Rosenberg et al. 2004, Rood et al. 2008). However, we also show that this preference may actually just be a selection effect, associated with the fact that BHk stars are intrinsically rare and thus can only be found in sufficiently large samples of stars.

2 THE CLUSTER SAMPLE

As the nomenclature of BHB, EHB and BHk stars is often unclear, and various authors might in fact talk about different stellar populations, it is essential to first make a clear definition of what we call EHB and BHk stars. This is best illustrated in the FUV CMD of NGC 2808 (Fig. 1 left panel, taken from Dieball et al. 2005). Various populations show up in the CMD and are marked with different colours, their corresponding counterparts are marked with the same colour in the optical CMD (Fig. 1 right panel, taken from Piotto et al. 2002). In this paper, we call those FUV sources EHB stars that are at least as blue as the ZAHB at $T_{\text{eff}} > 20000$ K (following e.g. Momany et al. 2004). Stars that are fainter than the EHB stars (i.e. below the ZAHB) but which have a similar colour in the FUV CMDs are the blue hook candidates (see also Brown et al. 2001). Stars brighter in FUV than the EHB stars might be AGB manqué stars. We see six such stars in our Fig. 1. The small population of stars bluer than the EHB stars and brighter than the BHk stars agree with being blue hook progeny.

BHk stars were first detected in ω Cen and NGC 2808 through the subluminous blue hook that these stars form at the hot end of the HB in the FUV CMDs. As Brown et al. (2001) point out, the higher $T_{\text{eff}}$ of BHk stars compared to the cooler EHB stars imply larger bolometric corrections in the optical and hence fainter optical magnitudes. As a result, the identification of BHk stars in optical CMDs is much more difficult. In constructing a parent sample of GCs for statistical purposes, the key requirement is that BHk populations, if present, could be identified with confidence. As already noted above, we therefore mainly restrict our sample to GCs for which sufficiently deep (space-based) UV data exist. We allow only two exceptions to this rule: M 54 and NGC 2419. BHk stars have been suggested in both of these clusters based on deep optical data, and we find these studies convincing. Our final parent sample is listed in Table 1, along with the relevant physical parameters for each cluster.

3 ANALYSIS

We searched for statistically significant differences between the parameters of the five BHk clusters and the 11 non-BHk clusters in the parent sample using a series of Kolmogorov-Smirnov (KS) tests. The KS test returns the probability that the difference between two populations should be as large as observed under the null hypothesis that both distributions are drawn from the same parent distribution. The results of the KS tests are given in Table 2. For reference, we have also carried out KS tests comparing our parent sample to the Harris (1996) catalogue of GCs in the Milky Way.

Table 2 shows that only very few statistically significant
Table 1. Properties of the Globular Cluster sample that were searched for BHk stars. The distance, reddening $E_{B-V}$, [Fe/H], specific RR Lyrae frequency $S$(RR), HB ratio $HBR$, the core, half-mass and tidal radii (columns 2 – 8), and the ellipticity, the logarithmic core and half-mass relaxation times, and the logarithmic central luminosity density (columns 11 – 14) are taken from Harris (1996). The concentration parameter $c = lg(t_{tidal}/t_{core})$ is given in col 10. The cluster mass and the central and half-mass escape velocities (cols 15 – 17) are taken from Gnedin et al. (2002). The collision rate $\Gamma \propto \rho c^2$ (Verbunt & Hut 1987, Heinke et al. 2003, Fregeau 2008), scaled with $\Gamma_{77,HC}$, is given in column 18; columns 19 – 22 indicate whether the cluster contains a BHB, EHB, BHk or multiple population, column 23 gives a lower limit to the number of BHk stars estimated from available CMDs. References for the BHk stars are (a) Brown et al. (1997, one spectroscopically confirmed BHk star, other than that no BHk population is visible), (m) Möller et al. (2004, 2007), (g) Dieball et al. (in prep.), (h) Ferraro et al. (1998), (i) Hill et al. (2002), (j) Knigge et al. (2002), (k) Landsman et al. (1996), (l) M"ol"er et al. (1997, one spectroscopically confirmed BHk star, other than that no BHk population is visible), (m) Möller et al. (2004, 2007), (n) mould et al. (1996), (o) Pascale et al. (1998), (p) Ripepi et al. (2007), (q) Rosenberg et al. (2004), (r) Sandquist & Hess (2008), (s) Watson et al. (1994, one subluminous HB star reported, possibly a BHk candidate, but other than that no BHk population was detected), (t) Zurek et al. (in prep.). (D) in column 22 indicates that the cluster was discussed in D'Antona & Caloi (2008) who suggest that the cluster contains a sizeable population of a second generation of stars.

Table 2. Probabilities returned from the KS test, given in %. We compare the various parameters (see Table 1) of the non-BHk clusters in our sample with the BHk clusters (column 2), and our parent sample including the BHk clusters with the Harris (1996) catalogue (column 3).

The correlations exist between the occurrence of BHk stars and the parameters of the clusters. As can be seen, the most significant difference between BHk and non-BHk clusters is associated with their mass distributions. More specifically, the KS test indicates at greater than 99% confidence that (high) mass is associated with the presence of BHk stars in a cluster. In Fig. we plot the mass distribution and the cumulative mass distribution for the BHk clusters (blue line), all clusters in our sample (red line), and all clusters from the Harris (1996) catalogue. As can be seen, all clusters in which BHk candidates have been found are amongst the most massive in the Galaxy. The apparent preference for BHk populations to be found in abnormally massive clusters has been remarked upon before in the literature (see e.g. KBBRH, RHBR, BHk, mp, #BHk

$M_{tot}$ $E_{B-V}$ $[Fe/H]$ $S$(RR) $HBR$ $r_c$ $r_{hm}$ $t_{tidal}$ $lg(r_c)$ $lg(t_{hm})$ $lg(BHk)$ $\Gamma$ $\rho_c$ $\rho_{hm}$ $\rho$ $\Gamma$ $\rho_{hm}$ $\Gamma$

NGC2419 84.2 0.11 -2.12 4.6 0.86 8.57 17.88 214.07 1.40 0.03 9.96 10.35 5.38 1.19 62.1 27.4 1.168
NGC2808 9.0 0.07 -1.52 2.9 0.96 0.08 2.44 20.71 2.50 0.01 5.62 8.83 5.41 0.18 39.3 17.3 0.183
NGC6752 4.5 0.04 -0.76 0.2 -0.99 0.52 3.65 56.11 2.03 0.09 7.96 9.48 4.81 1.50 68.8 38.1 0.004
NGC6441 11.7 0.47 -0.53 0.3 0.93 0.44 1.89 38.63 1.95 0.00 7.77 9.08 5.34 2.17 124.0 80.2 2.810
NGC6388 10.0 0.37 -0.61 2.4 0.35 1.95 18.06 1.70 0.01 7.74 9.01 4.91 0.32 40.7 26.1 0.081
M54 26.8 0.15 -1.59 6.1 0.75 0.86 3.82 58.24 1.84 0.06 8.46 9.62 4.58 2.59 84.5 51.6 1.230
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Figure 2. Top panel: Histogram of the logarithmic mass distribution of all clusters in our sample (red line), the BHk clusters (blue line), and all clusters in the Harris catalogue (black line). Bottom panel: Cumulative mass distribution of the sample clusters (red), the BHk clusters (blue), and the Harris catalogue (black).
the connection between bright low-mass X-ray binaries (LMXBs) and cluster collision rates. More specifically, they showed that LMXB-hosting clusters were uniformly distributed within the cumulative collision rate distribution of the Galactic GC sample.

Figure 3. Positions of the BHk clusters (blue) within the (normalized) cumulative mass distribution of all clusters (red) in our sample. If BHk stars scale with cluster mass, the BHk clusters should be evenly distributed.

4 DISCUSSION

Our main result is that BHk populations have so far been detected only in the most massive GCs, but this does not (yet) imply that low-mass clusters cannot form BHk stars. In particular, we cannot rule out that the apparent preference for massive GCs arises simply because these clusters contain more stars. Since studies of massive clusters thus typically also inspect more stars, such studies are more likely to turn up intrinsically rare populations, such as BHk stars. If, for example, only 1 in every 100,000 stars becomes a BHk object, individual low-mass clusters will not contain any BHk populations, even if there is no physical lower mass limit associated with BHk production.

The way to test for the existence of a critical mass limit in this type of analysis is to consider the location of BHk clusters in the sorted, cumulative mass distribution of the parent sample. If there is no critical mass limit, BHk clusters should be uniformly distributed within this cumulative mass distribution. If there is a mass limit, they should be significantly concentrated at the high mass end. By doing so, we are effectively combining many low-mass clusters to form aggregate high-mass clusters.

In Fig. 3 we plot the positions of the BHk clusters within the cumulative mass distribution of the available parent sample. Using a KS test, we then checked whether the positions of the BHk clusters is different from a uniform distribution. The returned probability that the BHk clusters are randomly selected from the parent population is 36.9%. This is not statistically significant at even the $1\sigma$ level of confidence. Thus, the available sample does not provide evidence for a lower mass limit for clusters capable of producing BHk stars.

Rosenberg et al. 2004, M"ohler et al. 2004, Rood et al. 2008). At first sight, this result would seem to support the self-enrichment scenario for BHk star production.

However, although BHk stars appear to be found more frequently in massive star clusters, this does not reveal much about their origin. In particular, there is an obvious selection bias resulting from the fact that massive clusters contain more stars. Since studies of massive clusters thus typically also inspect more stars, such studies are more likely to turn up intrinsically rare populations, such as BHk stars. If, for example, only 1 in every 100,000 stars becomes a BHk object, individual low-mass clusters will not contain any BHk populations, even if there is no physical lower mass limit associated with BHk production.

Other parameters for which the KS test suggested marginally significant differences between the BHk and the non-BHk clusters are the concentration parameter, the core and halfmass radius, the core and halfmass relaxation time, and the halfmass escape velocity. It is difficult to know whether these secondary correlations are physical, since most of the relevant cluster parameters also correlate with total cluster mass within our parent sample. If one is nevertheless willing to take these secondary correlations at face value, they might indicate that binarity may be a key ingredient in BHk star formation. More specifically, the long relaxation times, large core radii, small concentration parameters and large escape velocities of the BHk clusters might indicate that cluster core collapse was/is decelerated or prevented, most likely by the presence of binaries (e.g. Elson et al. 1987, Hut et al. 1992, Fregeau 2008). Although EHB stars seem to be rarely found in binaries (e.g. Moni Bidin et al. 2008) they still might have formed in binary systems and could be the result of binary evolution, much like their field counterparts, the subdwarf B (sdB) stars (e.g. Han et al. 2007). Binary interaction might then enhance mass-loss during the RGB phase of a star, finally leading to the evolution into a late He-flasher/BHk star (e.g. Bailyn et al. 1992). On the other hand, short relaxation times might imply that the hardening of binaries through binary interactions (Heggie 1975) occurs so rapidly that all of the stellar envelope is stripped while the star is still on the RGB, leaving behind a He WD rather than an EHB or BHk star.

Interestingly, most BHk clusters show multiple stellar populations (e.g. Cen, NGC 2808, M54) and/or unusual and tilted HBs (NGC 6388) that indicate He self-enrichment (see e.g. Lee et al. 1999, Bedin et al. 2004, D’Antona et al. 2005, Piotto et al. 2005, Siegel et al. 2007, Piotto et al. 2007). This may be linked to the high masses of the BHk clusters, as only clusters massive enough should be able to retain the ejecta of their AGB stars. However, so far no evidence for multiple, He-enriched stellar populations has been found in NGC 2419 (Sandquist & Hess 2008).

The primary result of our analysis is that from the available data one cannot conclude that a low mass cutoff to BHk populations exists. However, absence of evidence does not constitute evidence of absence. Such a low-mass cutoff may exist, and given that 4 of the 5 BHk clusters are the most massive in our sample, the BHk sub-sample could hardly be more biased towards high mass than it is. Thus the real problem is that the available sample is too small, and too deficient in lower mass clusters, to permit a more definitive test of the critical mass hypothesis. The available sample is itself strongly biased towards massive clusters (see the comparison of the parent sample to the total Galactic population in Table 2), but a larger more unbiased sample does not exist today. This is because massive clusters usually make more promising observational targets, for a variety of technical and physical reasons. However, this type of selec-

\textsuperscript{2} The same test was used by Verbunt \& Hut (1987) to establish the connection between bright low-mass X-ray binaries (LMXBs) and cluster collision rates. More specifically, they showed that LMXB-hosting clusters were uniformly distributed within the cumulative collision rate distribution of the Galactic GC sample.
4.1 Summary

BHk stars seem to be a rare phenomenon that occurs in only a few GCs. We have constructed a carefully selected parent sample of GCs in which the presence or absence of BHk populations can be established with confidence. BHk stars have so far been found in only the most massive GCs. However, we also find that this does not (yet) imply the existence of a lower limit on the mass of a cluster capable of producing BHk stars. Instead, the preference for massive clusters could just be a selection effect, associated with the fact that BHk stars are intrinsically rare and thus it is more likely to observe these stars in high mass clusters rather than low mass clusters. In order to resolve this issue, we need additional data on many more low-mass clusters.

Alternatively, it may be possible to make progress by studying how the numbers of BHk stars scale with cluster properties. However, given the non-uniformity of the existing dataset, we can only estimate lower limits based on the published data (see Table 1). In any case, the identification of high cluster mass as a necessary ingredient for the production of BHk populations appears to be premature.

We also note that not all massive clusters, or all clusters with multiple populations, also contain BHk stars. Counter examples are the massive GCs 47 Tuc and NGC 6441. On the other hand, NGC 2419 contains BHk stars, but apparently no multiple populations (see Sandquist & Hess, 2008). Therefore we conclude that mass might be the main, but not the only parameter relevant to establishing BHk populations in GCs. With this in mind, we have sketched a scenario for BHk formation involving dynamical interactions between binary systems that would also be consistent with the fact that BHk clusters tend to have long relaxation times, large core radii, and large escape velocities.

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REFERENCES

Bailyn, C. D., Sarajedini, A., Cohn, H., Lugger, P. M. & Grindlay, J. E. 1992, AJ, 103, 1564
Bedin, L. R., Piotto, G., Anderson, J., Cassisi, S., King, I. R. et al. 2004, ApJL 605, 125
Brown, T. M., Siveigart, A. V., Wayne B. L., & Hubeny, I. 2001, ApJ, 562, 368
Busso, G., Piotto, G. & Cassisi, S. 2004, MmSAI, 75, 46
Busso, G., Cassisi, S., Piotto, G., Castellani, M., Romaniello, M. et al. 2007, A& A, 474, 105
Connelley, J. L., Zurek, D. R., Shara, M. M., Knigge, C., Dieball, A. & Long, K. S. 2006, AAS 209.2608
Cordier D., Piotrinferni A., Cassisi S. & Salaris M. 2007, AJ, 133, 468
D’Alessandro, E., Lanzoni, B., Ferraro, F. R., Vespe, F., Bellazzini, M. & Rood, T. R., 2008, ApJ, 681, 311
D’Antona, F., Bellazzini, M., Caloi, V., Fusi Pecci, F., Galli, S. & and Rood, R. T. 2005, ApJ, 631, 868
D’Antona, F. & Caloi, V. 2008, MNRAS, 390, 693
D’Cruz, N. L., O’Connell, R. W., Rood, R. T., Whitney, J. H., Dorman, B. et al. 2000, ApJ, 530, 352
Dieball A., Knigge C., Zurek D. R., Shara M. M., Long K. S., 2005, ApJ 625, 156
Dieball A., Knigge C., Zurek D. R., Shara M. M., Long K. S., Charles P. A., Hannikainen D. C., 2007, ApJ 670, 379
Dorman, B., Rood, R. T. & O’Connell, R. W. 1993, ApJ, 419, 596
Elson R, Hut P. & Inagaki S. 1987, ARA&A, 25, 565
Ferraro, F. R., Paltrinieri, B., Fusi Pecci, F., Rood, R. T. & Dorman, B. 1998, ApJ, 500, 311
Fregeau, J. M. 2008, ApJL, 673, 25
Gnedin, O. Y., Zhao, H.S., Pringle, J. E., Fall, S. M., Livio, M. & Meylan, G. 2002, ApJ, 568, 23
Han, Z., Podsiadlowski, P. & Lyanas-Gray, A. E. 2007, MNRAS, 380, 1098
Harris, W. E. 1996 AJ, 112, 1487 (2003 compilation)
Heegue, D. C. 1975, MNRAS, 173, 729
Heinke, C. O., Grindlay, J. E., Edmonds, P. D. et al. 2005, ApJ, 625, 796
Hill, R. S., Cheng, K.-P., Smith, E. P., Hintzen, P. M. N., Bohlin, R. C. et al. 1994, AJ, 112, 601
Hut, P., McMillan, S., Goodman, J., Mateo, M., Phinney, E. S. et al. 1992, PASP, 104, 981
Knigge, C., Zurek, D. R., Shara, M. M. & Long, K. S. 2002, ApJ, 579, 752
Landsman, W. B., Siveigart, A. V., Bohlin, R. C., Neff, S. G., O’Connell, R. W. et al. 1996, ApJL, 472, 93
Lee, Y.-W., Joo, S.-J., Han, S.-L., Chung, C., Ree, C. H. et al. 2005, ApJL, 621, 60
Lee, Y.-W., Joo, J.-M., Sohn, Y.-J. et al. 1999, Nature, 402, 55
Lee, Y.-W., Demarque, P. & Zinn, R. 1994, ApJ, 423, 248
Möhlér, S., Heber, U. & Durrel, P. R., 1998, A&A, 415, 313
Möhlér, S., Siveigart, A. V., Landsman, W. B., Hammer, N. J. & Dreizler, S. 2004, A&A, 415, 313
Möhlér, S., Dreizler, S., Lanz, T., Bono, G., Siveigart, A. V. et al. 2007, A&AL, 475, 5
Momany, Y., Bedin, L. R., Cassisi, S., Piotto, G., Ortolani, S. et al. 2004, A&A, 420, 605
Moni Bidin, C., Catelan, M. & Altmann, M. 2008, A&A, 480, L1
Mould, J. R., Watson, A. M., Gallagher, J. S. III, Ballester, G. E., Burrows, C. J. et al. 1996, ApJ, 461, 762
Parise, R. A., Bohlin, R. C., Neff, S. G., O’Connell, R. W., Roberts, M. S. et al. 1998, ApJL, 501, 67
Piotto, G., King, I. R., Djorgovski, S. G. et al. 2002, A&A, 391, 945
Piotto, G., Villanova, S., Bedin, L. R., Gratton, R., Cassisi, S. et al. 2005, ApJL 621, 777
Piotto, G., Bedin, L. R., Anderson, J., King, I. R., Cassisi, S. et al. 2007, ApJL 661, 53
Ripepi, V. et al. 2007, ApJL, 667, 61
Rood, R. T., Beccari, G., Lanzoni, B., Ferraro, F. R., D’Alessandro, E. & Schiavon, R. P. 2008, MmSAI 79, 383
Rosenberg, A., Recio-Blanco, A. & Garcia-Marin, M. 2004, ApJ, 603, 135
Sandquist, E. L. & Hess, J. M. 2008, AJ, 136, 2259
Siegel, M. H., Dotter, A., Majewski, S. R., Sarajedini, A., M" ohler, S., Dreizler, S., Lanz, T., Bono, G., Sweigart, A. V. et al. 2007, ApJL, 661, 53
Chaboyer, B. et al. 2007, ApJ 667, L57
Verbunt, F. & Hut, P. 1987, in Helfand D. J., Huang J.-H., eds, Proc. IAU Symp. 125, The Origin and Evolution of Neutron Stars. Reidel, Dordrecht, p. 187
Watson, A. M., Mould, J. R., Gallagher, J. S. III, Ballester, G. E., Burrows, C. J. et al. 1995, ApJL, 435, 55
Whitney, J. H., Rood, R. T., O’Connell, R. W., D’Cruz, N. L., Dorman, B. et al. 1998 ApJ, 495, 284