A STAR IN THE M31 GIANT STREAM: THE HIGHEST NEGATIVE STELLAR VELOCITY KNOWN

NELSON CALDWELL
Center for Astrophysics, 60 Garden Street, Cambridge, MA 02138, USA
electronic mail: caldwell@cfa.harvard.edu

HEATHER MORRISON
Department of Astronomy, Case Western Reserve University, Cleveland, OH 44106-7215
electronic mail: heather@vegemite.case.edu

SCOTT J. KENYON
Center for Astrophysics, 60 Garden Street, Cambridge, MA 02138, USA
electronic mail: kenyon@cfa.harvard.edu

RICARDO SCHIAVON
Gemini Observatory, 670 N. A’ohoku Place, Hilo, HI 96720, USA
electronic mail: rschiavo@gemini.edu

PAUL HARDING
Department of Astronomy, Case Western Reserve University, Cleveland, OH 44106-7215
electronic mail: paul.harding@case.edu

JAMES A. ROSE
Department of Physics and Astronomy, University of North Carolina, Chapel Hill, NC 27599, USA
electronic mail: jim@physics.unc.edu

ABSTRACT

We report on a single star, B030D, observed as part of a large survey of objects in M31, which has the unusual radial velocity of $-780 \, \text{km \ s}^{-1}$. Based on details of its spectrum, we find that the star is an F supergiant, with a circumstellar shell. The evolutionary status of the star could be one of a post-main-sequence close binary, a symbiotic nova, or less likely, a post-AGB star, which additional observations could help sort out. Membership of the star in the Andromeda Giant Stream can explain its highly negative velocity.

Subject headings: Galaxies: individual (M31) – Galaxies: kinematics and dynamics – Stars: kinematics – Supergiants – circumstellar matter

1. INTRODUCTION

In large surveys, often a few objects will be found that are unusual in one respect or another. Our spectroscopic survey of candidate star clusters in the field of M31 (Caldwell et al. 2009) has provided such a case. From the 1400 objects observed, we expected (and found) a large number of misclassified stars, due to the heterogeneous quality of the imaging material used to identify cluster candidates.

All but a few of these stars are in the foreground, as revealed by their dwarf spectral types. Our catalog magnitude limit of $V=20$ required that any M31 stars observed would have to be bright giants or supergiants. Of the few stars we observed in that area that were clearly not from the foreground Milky Way disk, one star proved to be unusual in two ways: its spectrum is that of an F supergiant with weak Balmer emission, and its heliocentric radial velocity is $-780 \, \text{km \ s}^{-1}$, which is the most negative velocity yet found for a single star. The star is called B030D in the Bologna catalog of M31 objects (Galleti et al. 2007), and “Bol D30” in SIMBAD.

This star is unlikely to be a member of M31’s disk: it lies close to the center of M31 on the SW side, at a place where the heliocentric velocity of the disk is $-425 \, \text{km \ s}^{-1}$ (the minimum disk velocity for M31 reaches $-550 \, \text{km \ s}^{-1}$). A difference of even $230 \, \text{km \ s}^{-1}$ with respect to the disk circular velocity is much too high for any disk or thick disk star in M31. While M31’s halo velocity distribution is not well known, a velocity of $-480 \, \text{km \ s}^{-1}$ with respect to M31’s center (which has $V= -300 \, \text{km \ s}^{-1}$) is very high, even for a halo star.

Could it be an unusual star in the halo of the Milky Way? M31 lies at $l = 121.2$, $b = -21.6$. Accounting for the Sun’s motion with respect to the LSR and the LSR’s motion around the galactic center reduces the velocity to $-614 \, \text{km \ s}^{-1}$ with respect to the Milky Way center. A recent estimate of the Galaxy’s escape speed (544 km s$^{-1}$, Smith et al. 2007) suggests that it is unlikely that this star is bound to the Milky Way; and

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1. We have assumed that the Sun’s motion with respect to the LSR is $(U,V,W) = (-9, 12, 7) \, \text{km \ s}^{-1}$ and the LSR velocity is 220 km s$^{-1}$ (Mihalas & Binney 1981)
its highly negative velocity and galactic longitude imply that it cannot be a hypervelocity star ejected from the galactic center such as those identified by [Brown et al. (2009)].

This paper describes the analysis of the unusual spectrum of the star B030D and the reasoning that led us to conclude that the star is most likely a member of the M31 halo’s “giant stream” (Ibata et al. 2001) close to the pericenter of its orbit.

2. SPECTROSCOPY

B030D resides about 0.3° SW of the center of M31 (4 kpc in projection, see Fig. 1), and was originally cataloged by Battistini et al. (1981) as a “bluish and diffuse” object, based on photographic plates. It was first observed spectroscopically by us as part of our MMT Hectospec spectroscopic study of star clusters in M31 (Caldwell et al. 2009). From this good (but not ideal) spectrum we immediately realized that the object was not a star cluster, which is confirmed by the images made available as part of the Local Group Galaxy Survey (LGGS, Massey et al. 2006) see our Fig. 1. We also learned of its unusual velocity and estimated its spectral type to be F1, though its luminosity class was difficult to discern. The higher order Balmer lines were narrow, as would be the case for a low gravity star, but the H/3 absorption line was weaker than expected for such a star, and Hα was very weak.

We used the UBV photometry of Massey et al. (2006) to obtain more information about the nature of the star. Table 1 summarizes UBV photometry and other basic information on this star. Here we see that B030D has $V$=19.02. Figure 2 plots $U-B$ vs $B-V$ for all stars from the M31 catalog of Massey et al. (2006) with $V$ brighter than 19.5. B030D is shown by a large black circle.

Where do foreground stars from the Milky Way lie in this diagram? In this magnitude range, and at the relatively low galactic latitude of M31, we would expect to see stars from the thick disk and the halo of the Milky Way. The dashed line in Figure 2 shows the sequence of solar abundance main sequence stars from Fitzgerald (1970), reddened by the likely foreground reddening to M31, E(B-V)=0.13 (Massey et al. 2006). Metal poor dwarfs will be found above the dashed line, and indeed the sequence of Milky Way halo dwarfs can be seen above the line, terminating near $B-V=0.5$, $U-B=-0.15$. B030D’s $B-V$ is too blue to belong to the old halo of the Milky Way unless it is a field star blue straggler (e.g. Preston et al. 1994). Blue stragglers are metal-poor halo stars which are either significantly younger than most of the halo or the product of a merged binary. Judging from this diagram, B030D’s UBV colors are at best merely consistent with it being a main sequence star.

However, there are other options. Where do young supergiant stars from M31 appear in this diagram? Their position depends strongly on their reddening. Massey’s spectroscopically confirmed M31 O–F supergiants are shown in Figure 2 as red solid points, and the supergiant locus from Fitzgerald (1970) is shown as a solid black line. This locus has also been reddened by E(B-V)=0.13. The reddening line, plotted above the supergiants, shows where more highly reddened supergiants would appear in this diagram. It can be seen that most of the supergiants from Massey et al. are highly reddened early type stars. This is not unexpected: we would expect such young stars to be in dusty star forming regions and so be reddened by dust in both the Milky Way and M31. However more recently, Drout et al. (2009) have studied candidate yellow supergiants in M31, and have identified a number of stars with strong absorption from the triplet of O I 7774, a sensitive indicator of low surface gravity (Osmer 1972; Arellano Ferro et al. 2003). These stars are certainly members of M31, and are shown in Figure 2 as blue circles. Several of these stars have similar colors to B030D.

Unfortunately, B030D lies in the part of the $U-B$ vs $B-V$ diagram where the main sequence and the supergiant lines cross. Thus we see that the UBV colors of B030D are consistent with either a very low gravity star such as an M31 supergiant, albeit one with very little reddening from M31’s disk, or with a halo blue straggler from the Milky Way. (We have already noted, however, that its velocity is so high that if it were in the Milky Way it would be unlikely to be bound to our Galaxy.)

We subsequently observed the star with Hectospec in November 2007, along with a number of M31 stellar targets as comparisons, selected on the basis of color and magnitude to bracket the properties of B030D.

For the second set of observations we again used the Hectospec multi-fiber spectrograph on the MMT (Fabricant et al. 2005), with exposure time 4800s on target and 2400s off target to supply a local background to subtract from the spectra. The spectra were reduced in the standard way for fiber spectra (e.g., Caldwell et al. 2009), except that those off-target exposures were used as local backgrounds. The spectra have a resolution of 5.0Å and cover the region 3700-9200Å. We note that in regions where the bulge of M31 is prominent, such as is the case for B030D, not subtracting a local background can affect the derived velocity by as much as 100 km s$^{-1}$. Velocities were found using template spectra made from the M31 observations described in Caldwell et al. (2009). The spectra were flux-calibrated using spectra of flux standard stars, but for our comparison purposes here, we rectified the spectra using arbitrary but consistent continuum settings.

These comparison spectra help sort out the uncertainty in UBV diagram discussed above. Stars in the “main sequence” locus that starts at bottom right and reaches to the center of the UBV plot show the broad Balmer lines and weak gravity-sensitive lines typical of dwarf stars. Their velocities are consistent with membership of the thick disk and halo of the Milky Way, with the redder (closer) stars having thick disk kinematics and the bluer (more distant) stars having halo kinematics. Stars in the “supergiant” locus show narrow strong lines, and the presence of gravity sensitive lines such as Ti II, Fe II λ4471, Sr II λ4077, and the O I 7774 triplet. The velocities of those stars are consistent with membership of the M31 disk.

We selected a few spectra for detailed comparison here, based on the similarity of their UBV colors to B030D’s. These stars are shown in Figure 2 with large symbols. Figures 3 and 4 show the blue spectra of B030D compared to these M31 supergiants and Milky Way dwarfs, respectively. It can be seen that the Balmer lines of B030D are as narrow as those found in the M31 su-
pergians, distinguishably narrower than the foreground dwarfs. Also, the Ti II, Fe II λ4172 and Sr II λ4077 lines are readily apparent in B030D and difficult to see in the foreground dwarfs. Finally, the CH features contained in the G band are partially resolved in B030D, where the G band is visible in the foreground dwarfs, it is not resolved. All of these spectroscopic indicators suggest a low gravity for B030D. Note, however, the relatively weak Hβ line in B030D, compared to the other M31 stars.

Turning to the red parts of the spectrum (Figures 5 and 6), again we see that the O I λ7774 line is easily visible in B030D and the M31 supergiants, and absent or weak in the foreground dwarfs. Figure 7 shows the results of measuring the equivalent width of that line for all of our high S/N ratio stars, plotted against the ratio of the Ca II H&K line strengths (as a proxy for spectral type - the index saturates for spectral types later than G, Rosso 1994). G and K foreground dwarfs form the group around Ca II = 1.25 and O I = 0. The M31 F supergiants, along with B030D, clearly separate from the galactic mainsequence stars. In view of our qualitative approach here, we do not try to derive an accurate luminosity for B030D using the relationship between $M_V$ and O I λ7774 equivalent width derived in Arellano Ferro et al. (2003), but we note that their relation and our O I measurement gives an $M_V$ consistent with $-5.5$ (see below).

In summary, the spectroscopy confirms that B030D is a high luminosity star, at the distance of M31, not a main sequence star from the Milky Way halo. However, its lower order Balmer lines are unusually weak.

3. AN F SUPERGIANT WITH A SHELL

Though we have identified the star as an F supergiant, there remains the detail of the weak Balmer absorption. Figure 8 is an enlargement of the Hα part of the spectrum of B030D and a few comparison M3I F supergiants. Clearly there is blue-shifted Balmer emission at Hα in B030D, and that also explains why the Hβ line is weaker than expected. Since there are no accompanying forbidden lines, and moreover the offset exposures show no emission at all, we must assume the emission is not from the surrounding area but from the star itself, and likely due to a shell. Shell emission is common among the rare, luminous high-latitude Galactic F vari-
could rule out several alternatives. Infrared spectroscopy should provide a clear discriminant between a post-AGB star and a symbiotic nova. In a symbiotic nova, infrared spectra show strong CO absorption lines characteristic of red giant photospheres (e.g., Schild et al. 1992). In a post-AGB star, CO features at 2.3 and 4.6 μm suggest much cooler excitation temperatures (T \sim 300\,°K) expected from a circumstellar shell (e.g., Lambert et al. 1988; Hinkle et al. 2007).

There is one similar star we have observed in M31, with Hα in emission but no other nebular lines: f13633 (J004025.26+403926.9), which has the same luminosity but perhaps lower surface gravity than B030D. It is located in a one of the spiral arms, and appears to be double, in the LGGS image.

5. VELOCITY

We concluded in Section 2 that B030D is a high luminosity star at roughly the distance of M31. In Section 4 we went on to discuss four possible options: a very young, massive star type (a luminous blue variable) or three stellar types which are associated with older populations (a post-mainsequence close binary, a post-AGB star or a symbiotic nova).

Projected close to M31’s center but with a 355 km s\(^{-1}\) velocity difference with disk stars there (see 1), it would seem more reasonable to associate the star with M31’s halo. However, studies of the age distribution of M31’s halo show no evidence for very young stars (Brown et al. 2006), so if the star is a luminous blue variable, we need to seek possible mechanisms to accelerate a young disk star to such a high velocity. There are a number of such possibilities, such as the interaction of a binary with the super-massive black hole in the center of either M31 or M32, which would disrupt the binary and produce a “hyper-velocity star” (Brown et al. 2003), interactions in the core of a dense star cluster, or a “runaway” caused by a supernova explosion in a binary system (Leonard et al. 1993). While such interactions are likely to be very rare, they are not impossible.

However, there is a simpler, more likely explanation for the star’s large velocity which involves a well-studied component of M31’s halo, the Giant Stream, which was first discovered using star counts by Ibata et al. (2001). Subsequent kinematical studies (e.g., Merrett et al. 2003; Ibata et al. 2004; Merrett et al. 2006) have shown that the stream has a highly elliptical orbit with perigalacticon very close to M31’s center (within 2 kpc or less) and apogalacticon at 125 kpc (McConachie et al. 2003; Ibata et al. 2004; Fardal et al. 2007). Models fit to the stream have suggested velocities at its perigalacticon as low as V_{helio} = -900 km s\(^{-1}\) (Fardal et al. 2007). The planetary nebulae studied by Merrett et al. (2006) include ones that are possible stream members with V_{helio} as low as \sim -838 km s\(^{-1}\), although this PN has only one line at 4992A (from a Hectospec spectrum of ours), thus the possibility that the object is actually at high redshift cannot be dismissed. In Figure 9 we show velocities of PNe, drawn from Merrett et al. (2006) and our Hectospec observations (paper in preparation), along with the orbit of the stream proposed in Merrett et al. (2003). Clearly some PNe fall along the orbit of the stream, as does B030D.

Stars with masses of 3-4 M\(_\odot\) have main sequence life-times much shorter than the youngest stars in the Giant Stream. Thus, a post-AGB member of the Giant Stream with M\(_V\) = -5.5 is unlikely. However, B030D could be a post-AGB runaway star ejected from the disk of M31 at high velocity. In the Milky Way, 5% to 10% of 3-4 M\(_\odot\) B-type stars are runaways (Stone 1991). Although runaways with velocities of 200-300 km s\(^{-1}\) relative to the disk are rare (Stone 1991; Martin 2004), theoretical simulations produce high velocity runaways at the projected distance of B030D from the center of M31 (e.g., the Milky Way study of Bromley et al. 2009). In this case, B030D would have evolved into a post-AGB star after ejection as a runaway.

The post-AGB possibility seems remote and we conclude that the most likely origin for the star is as part of the Giant Stream. Brown et al. (2006) show that the stream contains stars as young as 4 Gyr, so the two older options discussed in Section 3 (a post-mainsequence close binary or a symbiotic nova) are the best possibilities.

6. SUMMARY

B030D is a curiosity. Not only does it have an extremely negative velocity, but it is an unusual and rare kind of star as well. In our research into spectroscopic databases, we could not find any exact analogues that matched the details of its spectrum with regard to the Balmer emission. That problem was certainly mostly due to the lack of modern, digital spectra of the classes of unusual stars described above, but the short life of this kind of F shell star must also be part of the story. In addition to IR observations, a further piece of data that may help to determine the exact classification would be the star’s variability. We examined the star on both epochs of the Palomar Sky Survey, but could not find a significant change in brightness over that period (36 years), though the different passbands used for the two surveys makes a comparison difficult. Modern digital images of M31 could of course provide more stringent limits on variability.

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Fig. 1.— Location of B030D in M31. The left image comes from a mosaic made from J band Digitized Sky Survey images, and covers 2.5°. The right image comes from a V band image of the Local Group Survey of Massey et al. (2006), and the field size is 30”. North is up, and east is to the left.

Fig. 2.— UBV colors of stars with $V < 19.5$ in the M31 field, photometry from Massey et al. (2006). No reddening corrections have been applied. Stars observed spectroscopically to be members of M31 are highlighted. Of those members, the ones whose spectra are shown in Fig. 3 and succeeding figures are further indicated with larger symbols. B030D is shown as a large filled circle. The sequence of dwarf stars (class V) and supergiants (Ia) are shown as dashed and solid lines, respectively, the data coming from Fitzgerald (1970) to which a reddening of $E(B-V)=0.13$ has been applied. The black arrow indicates the effect of a reddening of $E(B-V)=0.25$.

Fig. 3.— Blue spectra of M31 stars, membership being determined by velocity. Here we show spectra with Ca II ratios and/or color similar to B030D. Note the similar narrow widths of the Balmer lines, but also the weak H$\beta$ in B030D compared to its own other Balmer lines. The spectra in this figure and subsequent figures have had the continua removed for ease of display.
Fig. 4.— Foreground galactic stars, also determined by velocity, with Ca II ratios and colors similar to B030D. Note the much broader Balmer lines in the foreground stars.

Fig. 5.— Same as Fig. 3 in the red. Note the strong O I line in all these, indicative of very low surface gravity. Also note the filled-in Hα line of B030D, and the Hα emission for one other star plotted right above it. Neither star shows forbidden emission lines that would indicate a local HII region, such as is found in the third spectrum from the top, which reveals [NII] emission as well as Hα.

Fig. 6.— Same as Fig. 4 in the red. B030D has much stronger O I than the foreground stars.
Fig. 7.— Equivalent width of the O I λ7774 line vs the ratio of the Ca II H&K lines. The former is sensitive to surface gravity and the latter is a useful temperature index.

Fig. 8.— Hα spectrum, showing weak emission in B030D compared to other M31 member stars which have similar color and luminosity.
Fig. 9.— Velocities of PNe and B030D (dark square) plotted against distance along the major axis, for objects within 1 kpc of the major axis (|Y| < 1 kpc). The orbit for the M31 Giant stream proposed by Merrett et al. (2003) is also shown as a solid line, revealing that B030D can be considered part of the stream.
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| Object         | Massey(2006) ID | RA    | Dec    | Velocity | O−Ca | V   | B−V | U−B | V−R | R−I |
|----------------|----------------|-------|--------|-----------|-------|-----|-----|-----|-----|-----|
| M31 members    |                |       |        |           |       |     |     |     |     |     |
| B030D          | 004141.49+410308.2 | 0:41:41.5 | 41:03:08.0 | −780 ± 20 | −355 | 19.02 | 0.33 | 0.08 | 0.22 | 0.27 |
| f15459         | 004030.62+404523.8 | 0:40:30.6 | 40:45:23.8 | −559 ± 20 | −16  | 18.33 | 0.29 | 0.14 | 0.18 | 0.22 |
| y16803         | 004034.00+405358.3 | 0:40:34.0 | 40:53:58.3 | −505 ± 18 | −12  | 18.02 | 0.46 | 0.21 | 0.27 | 0.29 |
| f13633         | 004025.26+403926.9 | 0:40:25.3 | 40:39:26.9 | −640 ± 34 | −100 | 19.16 | 0.33 | 0.14 | 0.26 | 0.30 |
| f24367         | 004117.90+404845.0 | 0:41:17.9 | 40:48:45.0 | −510 ± 17 | −6   | 19.10 | 0.37 | 0.03 | 0.25 | 0.29 |
| y30936         | 004201.09+403951.9 | 0:42:01.1 | 40:39:51.9 | −419 ± 17 | −13  | 18.46 | 0.36 | 0.24 | 0.26 | 0.36 |
| Foreground     |                |       |        |           |       |     |     |     |     |     |
| a25217         | 004123.97+405249.0 | 0:41:24.0 | 40:52:48.7 | −51 ± 18  | ⋯    | 16.73 | 0.42 | −0.05 | 0.27 | 0.22 |
| f25865         | 004128.60+410229.6 | 0:41:28.6 | 41:02:29.6 | −63 ± 18  | ⋯    | 18.29 | 0.43 | −0.10 | 0.28 | 0.37 |
| f26766         | 004134.97+410537.0 | 0:41:35.0 | 41:05:37.0 | −76 ± 21  | ⋯    | 17.94 | 0.50 | −0.07 | 0.32 | 0.34 |
| f26781         | 004135.14+410116.3 | 0:41:35.1 | 41:01:16.3 | 9 ± 16   | ⋯    | 16.60 | 0.43 | −0.02 | 0.29 | 0.30 |
| f44756         | 004252.79+404605.6 | 0:42:52.8 | 40:46:05.6 | −63 ± 14  | ⋯    | 17.75 | 0.39 | 0.06  | 0.23 | 0.29 |

a Difference between the observed velocity and the computed local velocity of M31's disk.