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A SEARCH FOR YOUNG STARS IN THE HALO OF M31

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ABSTRACT

Previous studies have identified young hot stars that appear to have been formed in the halo of our Galaxy. Here we present preliminary results of a spectroscopic search for similar objects in the halo of M31. Radial velocities have been measured for 23 apparently blue objects (selected from APM measurements of Schmidt plates) in a magnitude range $B_v \simeq 17$–21. For one of these targets, AND 0029+413, the radial velocity suggests that the object is gravitationally bound to M31 and hence that it may be in its halo. However, recent CCD photometry for this object indicates that it is redder than implied by the original photographic observations. A number of possible scenarios are presented to explain this object, including one consistent with it being a young star in the halo of M31.

Subject headings: galaxies: individual (M31) — galaxies: stellar content — stars: early-type

1. INTRODUCTION

In spiral galaxies such as our own, most young B-type stars are found in the Galactic disk in open clusters or associations. The proximity of these structures to large, high-density molecular clouds of interstellar gas supports the view that star formation proceeds via the gravitational collapse of such material (Scoville, Sanders, & Clemens 1986). However, early investigations by Greenstein & Sargent (1974) as to the nature of blue stars at high Galactic latitude revealed a subset of stars with similar spectral and atmospheric characteristics to young B-type stars. Their average distance of 4 kpc from the Galactic plane places them well away from star-forming regions, and remote from large pockets of high-density interstellar gas. Recent improvements in astronomical instrumentation has allowed the observation of similar but fainter stars, such as PG 0832+676 (Brown et al. 1989), which appears to be a young B-type star 18 kpc from the plane. If these stars are indeed young hydrogen-burning objects, then their location far from the Galactic plane has to be explained.

Many of these objects can be understood in terms of ejection mechanisms, with the star being removed from its birth place in the galactic disk and accelerated to its current location by gravitational interactions with cluster members (Leonard & Duncan 1988) or by explosive supernovae events in a multistar system (Stone 1979). However, there exist several stars (Conlon et al. 1992) for which ejection from the disk cannot explain their large distances from the plane, as their evolutionary age is less than the time of flight needed for the star to travel from the disk to its current location. This result is surprising and implies that the stars must have formed in situ. Possible mechanisms are the condensation of infalling Galactic fountain material (de Boer & Savage 1984) or the interaction of small cloudlets of higher density interstellar gas (Dyson & Hartquist 1983). An alternative explanation is that these stars are subluminous and nearby (Carrasco, Aguillar, & Recillas-Cruz 1982), having spectra which mimic those of normal stars. These conflicting theories can only be definitively tested if the stellar distances and hence luminosities can be determined. This provides the motivation for our search for such objects in the halo of external spiral galaxies, the distances to which are known.

In the local group of galaxies, both M31 and M33 are candidates for such a search; however, M31 is more suitable, as the small inclination of 14°.2 (Walterbos, Brinks, & Shane 1985) of its disk to the line-of-sight allows us to survey the halo both above and below the disk. Additionally its distance modulus [$(m - M)_0 = 24.26$; Welch et al. 1986] means that horizontal branch (HB) and blue subdwarf (SdB) stars (a natural extension of the HB) in M31 will have apparent visual magnitudes of ~25 (Pritchet & Bergh 1988). Therefore subluminous stars in M31 can be eliminated from our target list by employing a photometric cutoff, which is in any case inherent in our plate material (see § 2.1). The remaining " blue" targets will consist of quasars, foreground stars such as white dwarfs and possibly luminous stars in the halo of M31. Only objects in the last group will normally have both a stellar spectrum and partake in the motion of M31 with its radial velocity of -300 km s^{-1} (Rubin & Ford 1970). Hence relatively low resolution spectra should allow us to distinguish luminous young objects in M31 from either foreground or background objects.

2. OBSERVATIONS AND DATA REDUCTION

Possible candidates for young blue stars in the halo of M31 were selected using plate photometry and then observed spectroscopically to determine their radial velocities. For one target, the radial velocity of which suggests an association with M31, additional CCD photometry was undertaken. Both the photometry and spectroscopy are described in detail below.

2.1. *Plate Photometry*

Ideally, selection of OB-type stars in M31 against the "backdrop" of a much larger population of Galactic foreground stars and background quasars, would be most readily accomplished from a *UBV* two-color diagram. However, the large extent of the halo of M31 (some 20 square degrees) necessitated the use of Schmidt telescope photographic plate material. Unfortunately, the only suitable plate material available to us came from glass copies of the Palomar Sky Survey of the 1950s, and from another plate taken on the Palomar Schmidt in 1970 using a IIIaJ emulsion and a Wratten 2c filter. The Palomar Sky Survey O (or " blue ") plate covers the $U + B$ passband and reaches to a limiting magnitude of 21.3; while

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the E (or "red") plate is directly equivalent to a Johnson R passband and reaches a limiting magnitude of 20.8. The IIIaJ plate plus filter covers the wavelength region 4400–5400 Å, which is approximately midway between the Johnson B and V passbands and had a limiting magnitude of 21.1. The plate scale for all plates is 67″.15 mm^{-1}.

The positions and O, B_v, and E magnitudes of stars in the vicinity of M31 were determined by measuring the available Palomar Schmidt plates on the APM facility at RGO Cambridge (see, for example, Irwin & Trimble 1984). Although the complete 36 square degree area of each plate was measured, only ~16 square degrees of the measured regions cover a common area due to the different plate centers. Objects identified from individual plates were matched onto a common coordinate system and the photographic magnitudes (with a typical accuracy of ±0.1 mag, although close to the plate limits the photometric errors increase to 0.25 mag) were calibrated using published stellar sequences around M31 (Humphreys, Sitko, & Sitko 1987).

The two-color diagram, shown in Figure 1*a*, was then used to select blue targets for spectroscopic observation (those to the left of the dotted boundary line). A magnitude range of $17 \leq B_v \leq 21$ was adopted, with the bright limit corresponding to the apparent magnitude of a bright supergiant at the distance of M31, while the faint limit (equivalent to the apparent magnitude of a B-type main-sequence star) was governed by the limiting magnitudes for the photographic pass bands. The candidates were partitioned into three zones (depicted in Fig. 1*b*), one in the disk and two in the halo at projected distances of more than 8 kpc from the major axis.

2.2. *CCD Photometry*

CCD photometry of AND 0029+413 was obtained on 1992 February 8 using the 1 m Jacobus Kapteyn Telescope on La Palma. The detector was a cooled coated GEC CCD of dimensions 590 × 400 pixels, with square pixels of size 0″.3 square. Exposures of 1200 s duration were obtained through KPNO B and V broad-band filters at an airmass of 1.5, with additional observations being taken of standard stars in the cluster M67 (Schild 1983) at various airmasses to enable extinction and zero points to be found. After bias subtraction and flat fielding, instrumental magitudes were measured using both the aperture photometry program PHOTOM (Eaton 1992), and the profile fitting techniques of DAOPHOT (Stetson 1987), with no significant differences being found. Color terms for this system were taken from Unger et al. (1988) to produce above atmosphere magnitudes on the standard system.

2.3. *Spectroscopy*

Spectroscopic observations were made using the 4.2 m William Herschel Telescope (WHT) at the Northern Hemisphere Observatory on La Palma, with the ISIS spectrograph, the R158B grating and the coated EEV CCD. A linear dispersion of 2.7 Å pixel^{-1} was obtained with a wavelength coverage of 3600–6650 Å. The two-dimensional images, which had been windowed to 1179 × 300 pixels, were reduced to a one-dimensional format using the Starlink spectral reduction package FIGARO (Shortridge 1986). A standard reduction method was used and included bias-correcting images, flat-fielding, removing cosmic rays, sky subtraction, and wavelength calibrating with CuAr exposures taken after each stellar exposure. Further details of the procedures used can be found in, for example, Lennon, Dufton, & Fitzsimmons (1992). Using DIPSO (Howarth & Murray 1988), another Starlink supported package, radial velocities were determined by cross-correlating the spectra of (normally B-type) standards with those of M31 targets (Simkin 1974). This technique gave a typical velocity resolution of 0.1 pixel (Irwin 1985) and hence allowed velocities to be determined to an accuracy of approximately ±30 km s^{-1}. To optimize the number of targets observed, a signal-to-noise ratio in the continuum of ~10 was

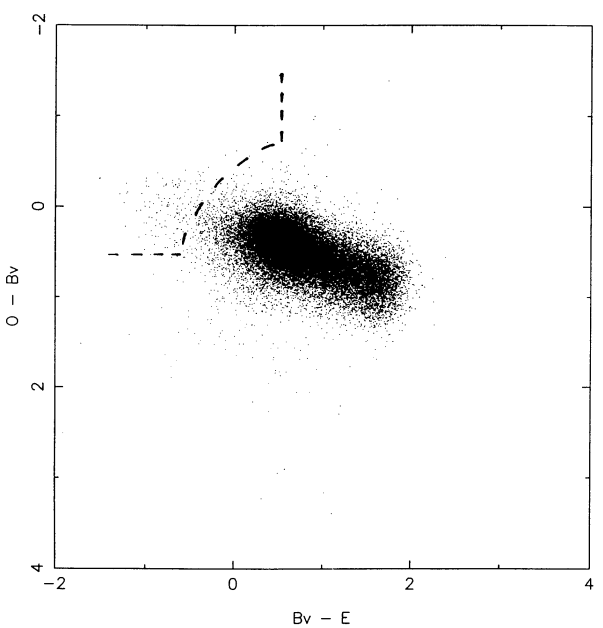

FIG. 1*a*

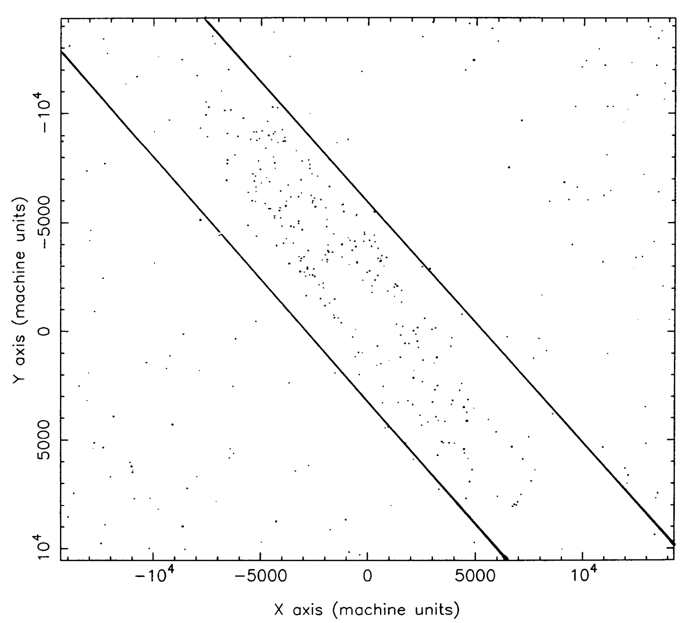

FIG. 1*b*

FIG. 1.—(*a*) Color-color diagram in O–B_v against B_v–E for targets along the line-of-sight to M31. Targets to the left of the dashed boundary were selected as blue targets to observe spectroscopically. (*b*) Isolated blue targets in the direction of M31, with the halo and disk segregated at 8 kpc form the major axis.

adopted as computer simulations showed that this was sufficient to give reliable estimates. Of the 104 possible halo targets, only stars in the southwest quadrant, which is approaching us, were observed; if the halo co-rotates with the Galactic disk, this would optimize the use of stellar radial velocities as a discriminant of membership of M31.

3. RESULTS AND DISCUSSION

In the direction of the halo of M31, 23 targets were observed spectroscopically. An observation was also made of a star (AND 0034+399) in the Galactic disk to act as a check on the reliability of the radial velocity measurements. Its measured velocity of -420 km s^{-1} supports the reliability of the velocity measurements and suggests that there is a velocity component due to the rotation of neutral gas in the disk. Most targets were either degenerate objects or quasars, but two possible normal stars were observed (see Table 1). For the latter, one has a radial velocity compatible with membership of M31 while the other, although having a small radial velocity has a spectrum similar to that of a normal B-type star. These stars will be discussed in detail below.

The star AND 0032+416 has measured photographic magnitudes O = 19.73, E = 20.08 and B_v = 19.65. The spectrum is similar to that of the B4V standard, HD 21996, which suggests that the star may be a young B star. However its radial velocity of -97 km s^{-1} does not appear consistent with its membership of M31. Hence although it may be at the distance of M31 but with a large peculiar velocity, it is more likely to be a SdB or BHB star in the halo of our own Galaxy.

For the other star (AND 0029+413), the spectrum was cross-correlated with those of both a B-type (HD 21996) and G-type (HD 186427) star (the reason for using a late-type standard will become apparent when the CCD photometry for AND 0029+413 is discussed). Figure 2 shows the WHT spectrum of AND 0029+413 in the region of Hα together with that of the G-type standard (wavelength shifted to a zero velocity frame); a significant blueshift is apparent for AND 0029+413, consistent with membership of M31. Cross-correlating its spectrum with those of the two standards implied heliocentric radial velocity estimates of -300 ± 30 km s^{-1} (for HD 21996) and -340 ± 30 km s^{-1} (for HD 186427). These values are consistent with the radial velocity of M31 at this position and implies that this star may be physically associated with M31. The photometric transformations of Evans (1988) applied to the photographic colors indicate a dereddened $(B-V)_0$ of -0.25 for this object. Combined with the measured Hα profile strength of 4.1 Å, a spectral type of approximately B2 V would be implied.

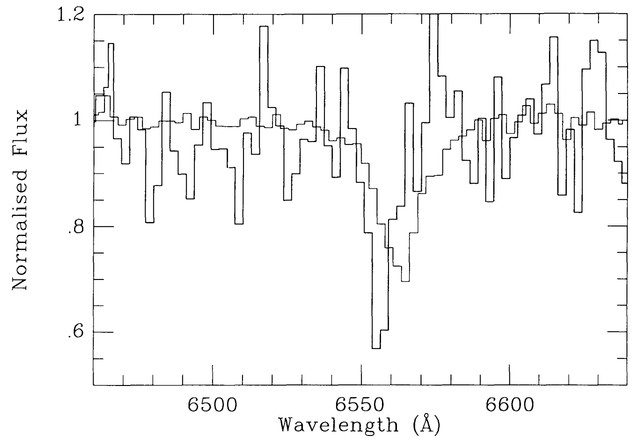

FIG. 2.—Hα region of AND 0029+413 (*bold histogram*) with the B-star standard HD 21996, clearly demonstrating the blueshift of AND 0029+413.

TABLE 1

STARS OBSERVED SPECTROSCOPICALLY AT WHT

Star Name	R.A. (1950)	Decl. (1950)	B_V	Type
AND 0049+395...	00ʰ49ᵐ52ˢ40	39°27′27″2	16.82	DB
AND 0046+398...	00 46 12.98	39 48 51.4	18.66	DA
AND 0049+394...	00 49 07.46	39 26 33.3	18.87	QSO $z = 1.8$
AND 0048+397...	00 48 01.74	39 44 25.2	19.51	QSO $z = 2.2$
AND 0047+394...	00 47 28.53	39 25 06.2	19.66	DA
AND 0047+397...	00 47 22.56	39 41 49.4	19.68	QSO $z = 1.1$
AND 0045+399...	00 45 53.62	39 53 27.6	19.74	QSO $z = 2.1$
AND 0029+409...	00 29 32.03	40 53 47.8	19.35	QSO $z = 1.0$
AND 0031+403...	00 31 49.91	41 17 07.9	18.66	DB
AND 0030+414...	00 30 00.46	41 24 28.0	19.40	DA
AND 0032+417...	00 32 19.57	41 41 21.7	19.60	QSO $z = 0.9$
AND 0032+416...	00 31 36.14	41 58 44.7	19.65	B/Sd B
AND 0031+417...	00 31 44.53	41 42 52.1	19.79	QSO $z = 2.3$
AND 0034+399...	00 34 27.53	39 51 45.9	18.60	B
AND 0034+419...	00 34 12.34	41 27 18.3	20.09	DA
AND 0048+394...	00 48 03.10	39 25 34.9	20.13	QSO $z = 0.8$
AND 0045+397...	00 45 13.07	39 39 47.7	20.16	QSO $z = 3.1$
AND 0043+396...	00 43 43.55	39 38 05.2	20.20	DB
AND 0040+396...	00 40 46.60	39 37 18.4	18.47	DA
AND 0040+394...	00 40 39.01	39 24 32.4	19.14	DA
AND 0029+422...	00 29 29.56	42 13 38.3	20.22	DB
AND 0030+419...	00 30 24.40	41 51 54.4	20.23	DB
AND 0029+413...	00 29 42.43	41 16 47.4	20.39	GO

In order to confirm the above result, additional CCD photometry was undertaken (see § 2.2). These observations indicate that AND 0029+413 is of a later spectral type than implied by the photographic photometry, with a measured $(B-V)_0 = 0.6 \pm 0.2$. For such values of $(B-V)_0$, hydrogen lines become temperature indicators, with the Hα strength implying a temperature of 6000 K from the calculations of Kurucz (1979). Given the poor signal-noise-ratio in the data it is not surprising that some G-type spectral characteristics initially went undetected. It was only when the relative flux distribution of AND 0029+413 and the G-type standard HD 186427 were compared that it became evident that AND 0029+413 was probably a late-type star. This is illustrated in Figure 3 where the spectrum of AND 0029+413 is plotted together with those of the standard stars. Although these are not spectrophotometric measurements, the flux distribution of AND 0029+413 is clearly more compatible with that of the G-type star. In addition G-type features such as the calcium H and K lines, the G-band and sodium D lines are just evident in the spectra of AND 0029+413. Together with the effective temperature implied by the strength of the Hα line, the presence of these lines indicate a spectral type of approximately G0.

The error between the photographic and CCD colors is almost certainly due to working near to the photographic plate limits, where the errors can rise to 0.25 mag per passband. Clearly, given that the "blue" nature of the other 22 candidates was confirmed spectroscopically, the photographic selection by color was generally very successful. It should not be too surprising, given the non-Gaussian errors associated with measuring magnitudes from photographic plates, that one of the 23 blue candidates observed turned out to be a late-type star.

The lack of a luminosity indicator complicates the discussion of the evolutionary status of AND 0029+413, but below we investigate a number of possibilities. Assuming it to

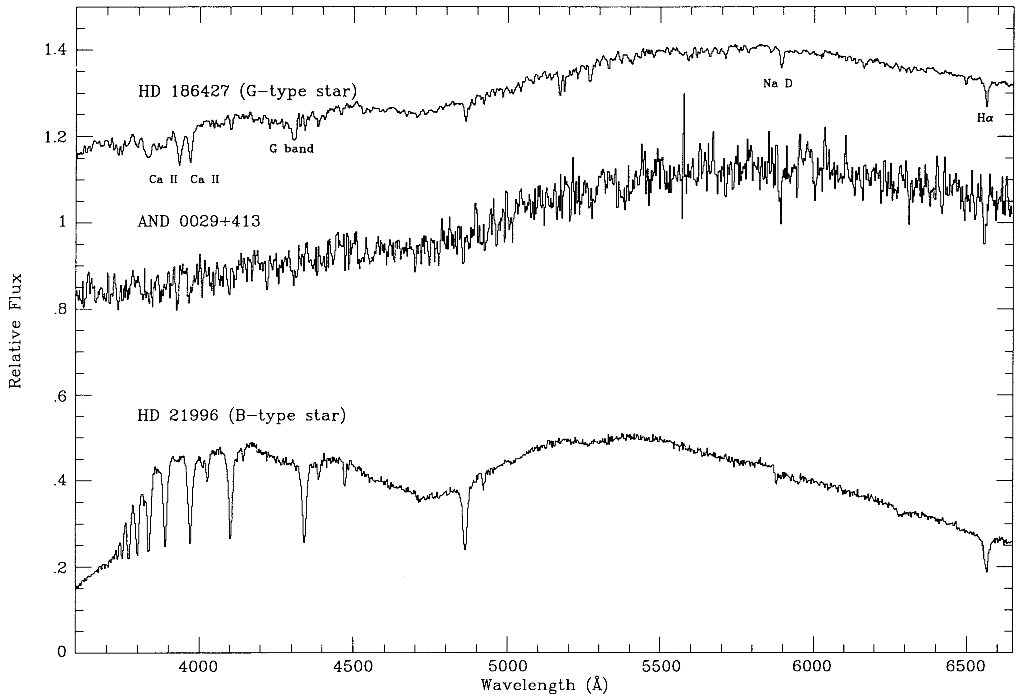

FIG. 3.—Spectra for AND 0029+413 and G-type (HD 186427) and B-type (HD 21996) standards. The spectra have been scaled so that their mean flux is approximately unity and then shifted so as to facilitate comparison.

be a main-sequence G-type star and adopting an absolute V magnitude of +4.4 (typical for G0 V; Jaschek & Jaschek 1990) this star would have a distance from the Sun of 16 kpc and be 21 kpc from the Galactic center. If AND 0029+413 was partaking in Galactic rotation, it would then have an observed radial velocity of approximately -120 km s^{-1}; hence its peculiar velocity relative to its local standard of rest would be ~ 200 km s^{-1}. This is likely to be an underestimate as it ignores any contribution from the transverse velocity and at the implied distance of AND 0029+413 from the Galactic plane (often described at the z-distance) of 5 kpc the halo may not be corotating with the disk. Also from its implied position in the galaxy it is possible to deduce a gravitational potential and therefore its Galactic escape velocity, which is ~ 70 km s^{-1} (Roy 1988). Hence if AND 0029+413 is a G0 V star in our own Galaxy, it would not be gravitationally bound, and since it has a negative radial velocity its origin would be particularly difficult to explain. In addition, it seems improbable that while surveying a relatively small spatial area in the direction of M31, we should identify a Galactic object with the same velocity as M31. For these reasons we believe that this star is probably not a G0 V star in our Galaxy but that it may be associated with the halo of M31.

At the distance of M31, AND 0029+413 would have an absolute V magnitude of -4.3 and, adopting a bolometric correction of -0.1 for a star at 6000 K, the implied luminosity is log $L/L_{\odot} = 3.6$. There are then at least two possible evolutionary histories. One is that AND 0029+413 is evolving blueward along the post–asymptotic giant branch (PAGB), in the transition from the AGB to the planetary nebulae stage. Second, the star may be evolving redward from the hydrogen-burning main sequence, implying that it is still a relatively young object. If it is a PAGB star in the halo of M31 then its luminosity, ignoring any interstellar extinction, implies that the star would be lying near the 0.56 $M_{\odot}$ PAGB evolutionary track of Schönberner (1983). As the star would have recently left the AGB, it might still be enshrouded in circumstellar dust and gas due to mass-loss phases on the AGB (see Iben & Renzini 1983 for details). An infrared excess would confirm the PAGB nature of this object and should be similar to the infrared excesses found in other PAGB stars of similar temperatures, such as RV Tau (Trams 1991). Unfortunately such observations are not currently possible on a star of this brightness.

Considering the second possibility, that the star has evolved from the hydrogen burning main sequence redward to its current status as a G0 II star, the evolutionary tracks of Maeder & Maynet (1988) imply that the progenitor for this object would be a 7 $M_{\odot}$ B2 V star. AND 0029+413 would then have an age (measured from its arrival on the zero-age main sequence) of ~ 50 million years. If it lies directly above the major axis of M31 it would be ~ 22 kpc from the Galactic plane. However, due to the inclination of the disk there may be a projection effect; adopting an angular extent of 3°3 (Holmberg 1958) for M31, leads to an uncertainty in the estimate of the distance from the M31 Galactic plane of approximately ± 5 kpc. Clearly, even after taking projection uncertainties into account, AND 0029+413 would still be far from star-forming regions in the disk of M31. Hence since M31 has a similar morphology to our own Galaxy, if AND 0029+413 has evolved from an early B-type star, this would reinforce the premise that young hydrogen-burning B-type stars can indeed exist far from the Galactic plane.

4. CONCLUSIONS

Further observations of AND 0029+413 are required to confirm its true nature. These may involve the observations of near-infrared features such as the Ca I triplet (at $\sim$8500–8600 Å) and the Mg I singlet (8807 Å) which can be used in G-type stars to determine the luminosity, temperature, and metallicity (Diaz, Terlevich, & Terlevich 1989).

Although we have been unable to confirm the presence of young B-type stars in the halo of spiral galaxies, we have shown that the technique can eliminate both foreground and background targets toward M31. The velocity resolution has allowed us to isolate one object with the radial velocity of M31, the true nature of which cannot unfortunately be resolved with the current observations. We intend to obtain CCD photometry for our remaining 78 blue targets, in order to better determine their colors and refine an object list suitable for spectroscopy.

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