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Faint High Latitude Carbon Stars Discovered by the Sloan Digital Sky Survey: Methods and Initial Results

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ABSTRACT

We report the discovery of 39 Faint High Latitude Carbon Stars (FHLCs) from Sloan Digital Sky Survey commissioning data. The objects, each selected photometrically and verified spectroscopically, range over $16.6 < r^* < 20.0$, and show a diversity of temperatures as judged by both colors and NaD line strengths. Although a handful

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of these stars were previously known, these objects are in general too faint and too warm to be effectively identified in other modern surveys such as 2MASS, nor are their red/near-IR colors particularly distinctive. The implied surface density of FHLCs in this magnitude range is uncertain at this preliminary stage of the Survey due to completeness corrections, but is clearly >0.05 deg^{-2}. At the completion of the Sloan Survey, there will be many hundred homogeneously selected and observed FHLCs in this sample.

We present proper motion measures for each object, indicating that the sample is a mixture of extremely distant (> 100 kpc) halo giant stars, useful for constraining halo dynamics, plus members of the recently-recognized exotic class of very nearby dwarf carbon (dC) stars. The broadband colors of the two populations are indistinguishable. Motions, and thus dC classification, are inferred for 40-50% of the sample, depending on the level of statistical significance invoked. The new list of dC stars presented here, although selected from only a small fraction of the final SDSS, doubles the number of such objects found by all previous methods. The observed kinematics suggest that the dwarfs occupy distinct halo and disk populations.

The coolest FHLCs with detectable proper motions in our sample also display multiple CaH bands in their spectra. It may be that CaH is another long-sought low-resolution spectroscopic luminosity discriminant between dC's and distant faint giants, at least for the cooler stars.

Subject headings: astrometry – stars: carbon – stars: statistics – surveys

1. Introduction

Although stars with prominent C_2 in their spectra have been observed for more than a century, faint high-latitude carbon stars (hereafter FHLCs), where here we arbitrarily define "faint" as $R > 13$, prove to be of very current and special interest for a variety of oddly unrelated reasons. Such objects are rare: certainly $< 10^{-5}$ of random stellar images prove to be C stars. Thus FHLCs are, for example, rarer than QSOs at a given magnitude. They are also not particularly easy to discover: although the cool N-type stars (with apologies to Keenan (1993) for the outdated nomenclature) do have very red colors, the considerably more numerous R and CH stars do not. Although some FHLCs are found serendipitously, the majority of past discoveries have been due to objective prism surveys such as those at Case (Sanduleak & Pesch 1988), Michigan (MacAlpine & Williams 1981), Kiso (Soyano & Maehara 1999), Byurakan (Gigoyan et al. 2001), and Hamburg/ESO (Christlieb et al. 2001). Recent attempts at automated photometric selection of FHLCs have met with some success for the very red, cool N stars (Totten & Irwin 1998; Totten et al. 2000; Ibata et al. 2001), but again the warmer, more numerous FHLCs have still proven difficult to select autonomously (Green et al. 1994). Although $\sim$ 7000 galactic carbon stars are known (Alksnis et al. 2001), the sum of all the heterogeneous investigations discussed above has probably yielded only a few hundred FHLCs.

Why are we interested in finding these rare FHLCs, especially as essentially all are too faint for the high dispersion spectroscopic analysis that has been at the core of the study of red giants thus far? It has become clear in the past decade that the FHLC population consists of two totally distinct, physically unrelated classes of objects which (confusingly) share remarkably similar colors and (at least at moderate resolution) spectra. Both of these two classes are interesting.

Some fraction of the FHLCs are exactly what they appear to be: distant, luminous evolved giants in the halo. There have been a small handful of previous hints that this population extends to rather astonishing distances. For example, Margon et al. (1984) serendipitously found one such star at $d \sim 100$ kpc. Clearly the presence of a brief-lived phase of stellar evolution at these galactocentric distances poses interesting questions of origin: could there be star formation in the distant halo, or in infalling gas? Are these the most luminous members of previously-disrupted dwarf satellites? Moreover, aside from the question of the origin of the luminous FHLCs, they make splendid halo velocity tracers (Mould et al. 1985; Bothun et al. 1991), as at these huge distances they almost surely encompass the entire dark matter halo, and the very sharp C_2 band heads make radial velocity determinations straightforward even at modest sized telescopes.

The remainder of the FHLCs are perhaps even more exotic. They exhibit large proper motions (Deutsch 1994), and in some cases parallaxes (Harris et al. 1998), that place them at main sequence luminosity ($M_V \sim 10$). These so-called "dwarf carbon stars", hereafter dC's, should be an oxymoron, as there should be no way for C_2 to reach the photosphere prior to the red giant phase. For 15 years, precisely one such star was known, G77-61 (Dahn et al. 1977; Dearborn et al. 1986), but Green et al. (1991) and Green & Margon (1994) showed that these are in fact a surprisingly common subclass of FHLCs, unnoticed in the past simply as most have $R > 16$. A recent review of the dC stars has been given by Green (2000). The dozen or so known previous to this work are all at $d < 100$ pc, a volume that contains not a single giant C star. Therefore, contrary to the conclusions of 100 years of classical astronomical spectroscopy, the overwhelming numerical majority of stars with C_2 in their spectra are in fact the previously unknown dwarfs, not giants! Current thinking is that the C_2 in dC's was deposited in a previous episode of mass-transfer from a now invisible, highly-evolved companion. In this respect the dC's are probably similar to barium stars, and in particular to the so-called "subgiant CH stars" (Bond 1974). Those objects, which despite their names at least occasionally have near main sequence luminosity, are presumably slightly too warm to show strong C_2 despite the inference of $C/O > 1$.

Aside from the usual invisibility of the evolved companion, great age for the dC stars is also implied by the extraordinarily metal poor composition inferred for the prototype, G77-61 (Gass et al. 1988). Thus the ultimate significance of these stars might be to call attention to otherwise elusive Population III objects (see also the discussion of Fujimoto et al. (2000)). Furthermore, if an early generation of stars is responsible for reionization of the intergalactic medium, as now seems increasingly likely (Madau et al. 1999; Fan et al. 2001; Becker et al. 2001), then the early Universe achieves a heavy element abundance already substantially above that inferred for the dC prototype, perhaps implying that objects such as these are actually pregalactic (Rees 1998).

Despite the totally different nature of the giant and dwarf C stars, the spectra and colors of the disparate classes are frustratingly similar. Indeed, although some preliminary photometric and spectroscopic luminosity criteria have been suggested (Green et al. 1992; Joyce 1998), dC's are currently identified with complete confidence only if they show detectable parallax or proper motion, thus ruling out membership in the distant halo.

The wide areal coverage (10^4 deg^2), faint limiting magnitude ($m \sim 22$), precision five-color photometry (~ 0.02 mag), and highly multiplexed spectroscopic capabilities of the Sloan Digital Sky Survey (York et al. 2000) provide the opportunity to identify large numbers of new FHLCs, providing far larger samples than currently available, both for use as halo dynamic probes and to elucidate the nature of the engimatic dC's. In addition to merely extending the catalogs of both classes, major goals of this work are also to develop and/or refine photometric and spectroscopic luminosity discriminants, hopefully apparent at low to moderate resolution, and to understand the ratio of dwarfs to giants in a magnitude limited sample.

Here we report initial results of a search for FHLCs in the SDSS commissioning data. This subset of SDSS data is very similar, although not quite identical to, the SDSS Early Data Release (EDR), and the reader is referred to Stoughton et al. (2002) for a detailed description of those data and their reduction. Our results therefore utilize only $\sim 5\%$ of the eventual Survey, but should serve to illustrate the potential of SDSS to elucidate many issues related to the FHLC problem. This paper concentrates on methods of selection, and an overview of the first photometric, spectroscopic, and astrometric results, to give the reader an understanding of the nature of SDSS FHLC data. A more lengthy analysis of astrophysical implications will appear in later publications.

2. Observations

2.1. Selection of Candidates

Analysis of imaging data from the SDSS camera (Gunn et al. 1998; Lupton et al. 2001) provides an imaging data base in five broadband filters (Fukugita et al. 1996). The SDSS photometric calibrations are described in Hogg et al. (2001) and Smith et al. (2002). Unusual stellar objects of a large variety of types are chosen for spectroscopy via automated analysis of this data base, normally on the basis of odd colors which imply that the object is interesting. In the case of FHLCs, the SDSS target selection algorithm was constructed via observation of a large number of previously known FHLCs in the SDSS color system (Krisciunas et al. 1998) prior to the beginning of observations with the SDSS telescope. That work showed that although R-type FHLCs are normally rather close to the normal stellar locus in SDSS colors, they may still be separable in a photometric data base that is sufficiently precise and homogeneous. This is not obvious *a priori*: the broadband colors of many of these objects are far from extraordinary, often corresponding to spectral types of mid-K. Krisciunas et al. (1998) did not target the very red, cool N stars: although far more distinct in color space, they are even rarer than the R stars which are the focus of this paper.

The basic FHLC photometric target selection algorithm currently in use by the Survey relies mainly on the separation of carbon stars from the stellar locus evident in the $(g - r)$ vs. $(r - i)$ diagram[17] (Krisciunas et al. 1998). Objects with stellar morphology, and meeting several criteria that assure reliable photometry, are selected as candidate carbon stars if they have $15.0 < r^* < 19.5$ and fall in the region below $(r^* - i^*) < a + b\ (g^* - r^*)$, where $a = -0.4$ and $b = 0.64$. In addition, candidates targeted for spectra must be at least as red as $(g^* - r^*) > 0.85$, $(r^* - i^*) > 0.05$, and $(i^* - z^*) > 0.0$. Candidates with $(g^* - r^*) > 1.4$ are given higher priority for spectra, as they are generally separated further from the stellar locus in $(g^* - r^*)$ vs. $(r^* - i^*)$. Finally, we also allow for selection of very red carbon stars (*e.g.*, those with dust), considering as candidates stars with $(g^* - r^*) > 1.75$. Note that the precise values of color-selection regions for carbon stars have varied somewhat during the SDSS commisioning phase.

The bright cutoff in the selection criteria is imposed by loss of photometric data due to saturation in the imaging portion of the Survey, as well as risks of scattered light contamination of fainter objects during spectroscopy. The most sensitive observations, in gri, saturate at $m \sim 14$ in the imaging data. The faint cutoff is chosen to yield a spectrum of reasonable classification quality during the 45-minute Survey spectroscopic exposures. This is a fainter limit than any previous wide-area survey for FHLCs. Even the faintest objects in our sample are sufficiently well-exposed in the imaging data that there should be few if any instances of image misclassification (*e.g.*, a galaxy selected as a candidate), although we of course have no defense against visual binaries unresolved in the Survey images.

A further complication, but overall a bonus, in our automated target selection is that the region in SDSS color space that we select for FHLCs partially overlaps the target selection region for high redshift QSOs (Richards et al. 2002), which have a higher priority for spectroscopic followup in the Survey. Therefore some candidates which we target as FHLCs have already been selected for spectroscopy on unrelated grounds. Although this complicates calculations of the ultimate detection efficiency, it increases the total yield for at least two reasons: far more spectroscopic fibers can be allocated to QSO candidates than to FHLCs, and FHLCs which prove to lie just barely outside of our preset target selection colors may still lie within the QSO color regions, and therefore be selected for spectroscopy regardless.

Like all other surveys, ours most certainly has selection biases, and FHLCs of colors markedly divergent from the known ones which shaped our target selection algorithms may escape detection (although some may be recovered by the QSO survey, or via "serendipity" target selection, which

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[17] The current, preliminary nature of the SDSS photometric calibration requires unfortunately cumbersome notation. The SDSS filter system defined by Fukugita et al. (1996) is denoted $u'g'r'i'z'$, but unfortuntaely differs significantly from the filters as realized on the 2.5m telescope, where the filters and bandpasses are denoted as $ugriz$. However, photometry obtained at this early stage of SDSS is denoted $u^*g^*r^*i^*z^*$ to stress the preliminary nature of the calibration.

searches for objects with unusual colors). Consequently certain derived quantities from this work, *e.g.*, surface densities, must be regarded as lower limits. However, the results below, which show a relatively broad range of temperatures in our FHLC sample, as well as surface densities higher than those derived by previous work, give us some confidence that our target selection criteria alone are at least not more biased than previous efforts, and hopefully somewhat orthogonal thereto. Theoretical evolutionary studies imply a surface density indicating that previous observations must have missed a substantial fraction of dC's (deKool & Green 1995), and it is easy to identify many potential biases quite aside from limiting magnitude. For example, previous objective prism selection of FHLCs often required that prominent C_2 bands appear on the IIIaJ photographic emulsion, certainly a bias towards warmer objects. The fact that all three dC's with measured parallaxes have essentially the identical M_V, $(B-V)$, and $(V-I)$ (Harris et al. 1998) is a further hint that current samples are badly biased.

Certainly we expect to recover most or all of the previously known FHLCs with $m>16$ that lie in the SDSS area. Unfortunately these are sufficiently rare objects previous to our work that there have been only a handful of such opportunities at this relatively early stage of the SDSS. A further complication is that many objects cataloged in previous surveys are bright enough to cause saturation problems in SDSS. We do recover the N-type FHLC 1249+0146 listed by Totten & Irwin (1998). Another field already covered in commissioning data that happens to also be rich with FHLCs is the Draco dwarf spheroidal galaxy. Here we successfully (and autonomously) recover three previously known FHLCs, as well as discover a new, previously uncataloged object (see §5). However, our target selection algorithms did fail to flag two other previously known FHLCs that do lie in our data, the relatively bright $(17 < r^* < 18)$ stars Draco C2 and C3 (Aaronson et al. 1982; Armandroff et al. 1995). Post-facto examination of the SDSS photometry for these two stars shows that they just barely missed selection, lying a few hundredths of a magnitude too close to the normal stellar locus in $(g-r)$ versus $(r-i)$ space. The former object *was* flagged as a high-z QSO candidate, however, and may well eventually receive a spectrum on those grounds, erroneously motivated though they may be, and thus ultimately join the list of successful recoveries. This example illustrates that even given the precise, homogeneous nature of SDSS photometry, automated target selection remains an inexact science, and conclusions which rely on completeness, rather than lower limits on surface density, must be treated with great caution.

As expected from the target selection criteria (above), we do find that a major contaminant in our survey for FHLCs (aside from unexpectedly large photometric errors in otherwise normal stars) are QSOs in the $2.5 < z < 4$ range (Schneider et al. 2002). A number of DQ white dwarfs (degenerate stars with strong C_2 bands) have also been found, and will be discussed elsewhere.

Although the SDSS in spectroscopic mode obtains more than 600 spectra simultaneously, and ~ 5000 spectra on one clear winter night, at the end of the 10^6 spectra which constitute the project, observations will cease permanently. Thus spectroscopic targets are a finite and valuable resource. However, the rarity of even FHLC candidates, much less actual FHLCs, is such that this effort is a trivial perturbation upon the SDSS. The photometric target selection typically yields one candidate

FHLC on each 7 deg^2 spectroscopic field, and thus the program uses $< 0.5\%$ of the spectroscopic fibers. The completeness of this program is however irrevocably limited by two further factors, one mechanical and the other programmatic. The minimum spacing of two spectroscopic fibers projects to $55''$ on the sky, and a candidate in close proximity to an object with higher scientific priority, typically a galaxy or QSO candidate, cannot be observed. In addition, there may be regions where all available fibers for a given spectroscopic exposure are occupied by higher priority programs. In both such cases, of course, promising candidates identified by the target selection algorithms may later be observed spectroscopically at other telescopes.

2.2. Spectra of Faint High Latitude Carbon Stars

At the time of this writing, spectra have been obtained of several hundred objects that meet the FHLC target selection criteria. A significant fraction of these objects simultaneously meet the color selection criteria for other, scientifically-unrelated SDSS programs, especially high redshift QSOs as noted previously, and were selected for spectroscopy for those programs rather than specifically to discover FHLCs.

2.2.1. Details of Observations

All but one of the spectra discussed here were obtained with the SDSS 2.5m telescope as part of the spectroscopic survey. These observations, obtained with a set of plug plates and fiber-fed CCD spectrographs, cover the 3800 – 9200 Å range with $\lambda/\Delta\lambda \sim 1800$, and are typically exposed for 45 min (as the sum of three individual spectra), following constraints set by other SDSS scientific programs. The reduction and calibration of the spectra are described by Stoughton et al. (2002). The objects discussed in this early report were extracted from the reduced spectra via manual, independent examination of the spectra by multiple of the authors. In addition, an unpublished code under development by D. Schlegel selected FHLC candidates via a comparison with a series of SDSS spectral templates.

A handful of particularly faint photometric candidates were spectroscopically observed with the Double Imaging Spectrograph of the ARC 3.5m telescope or the Low Resolution Spectrograph of the Hobby-Eberly Telescope (HET), although all but one of the final sample discussed here ultimately received a workable 2.5m spectrum as part of the continuing SDSS program.

2.2.2. Identification of New FHLCs

On the basis of the above spectra, thirty-nine of the SDSS candidates observed prove to be FHLCs. These spectra are shown in Figure 1, and basic astrometric and photometric data are given in Table 1. Most of the spectra are qualitatively similar to those of the brighter, objective-prism selected FHLCs in the literature (Green & Margon 1990; Bothun et al. 1991; Totten & Irwin 1998), dominated by strong C_2 Swan bands at $\lambda\lambda$4737, 5165, and 5636, as well as the red CN bands ($\lambda\lambda$7900, 8100). Closer examination of the spectra, however, shows a richness not present in previous FHLC investigations: for example, there is a broader range of NaD strength (presumably due to a larger range of T_{eff}) than present in previous samples, consistent with our freedom from some previous observational selection effects. In particular, most photographic surveys in practice required that the Swan bands be well-exposed and prominent on the F or J emulsion, implying that objects with colors in the mid-G to mid-K range were normally favored, even if the C_2 and CN bands could be expected over a broader temperature range, as we now find.

Balmer emission, while not common in C giants, is certainly not unprecedented, and about the same fraction of our sample shows Hα in emission as the sample of bright giants observed by Cohen (1979). Individually interesting objects will be discussed in more detail in §5 below.

Figure 2 displays color-color diagrams of the SDSS FHLCs, as well as that of $\sim 10^4$ anonymous faint field stars, to define the normal stellar locus. The observed range of $0.8 < (g^* - r^*) < 2.0$ for the new FHLCs corresponds roughly (Fukugita et al. 1996) to $1 < (B - V) < 2$, *i.e.*, includes objects with colors ranging from early K through M stars. Thus many of these objects are not extraordinarily red, and are not selected by methods tuned to red excesses. The FHLC survey of Totten & Irwin (1998), for example, finds stars chiefly with $(B - V) > 2.4$. The large scatter in the observed $(u^* - g^*)$ colors in our data is due to the lower sensitivity of the Survey in the u band combined with the faintness of most of the stars in the sample. Indeed, many of the stars are not confidently detected at u. A few objects with unusual colors are noted in §5.

SDSS coordinates are generally of $0\farcs1$ rms accuracy in each coordinate in the ICRS frame, but a large fraction of these stars (see §3.2) prove to have significant proper motions. Therefore we provide finding charts for our sample in Figure 3. The epochs of the images vary slightly, but all lie within one year of 1999.5.

Our automated target selection algorithms have thus far identified few of the cooler, extremely red FHLCs (presumptively all giants), in agreement with the expectations from previous work that they are of relatively low surface density (Totten & Irwin 1998). One such example is the Totten & Irwin (1998) object noted in §2.1, with $(g^* - r^*) = 3.60$ in our data. However, in an unrelated search of very red objects appearing simultaneously in SDSS and 2MASS, we have found two further such stars, SDSS J122740.0-002751 and J144631.1-005500; they are bright ($r^* = 17.03$ and $r^* = 15.21$, respectively), and redder than almost any of our automatically selected sample ($(g^* - r^*) = 2.76$, $(g^* - r^*) = 2.19$). Their spectra, obtained at the ESO NTT and displayed in Figure 4, are conventional; the brighter object displays $H\alpha$ emission, consistent with a giant classification. As these are not homogeneously selected and may be of quite different physical nature, we do not discuss these objects further here (although some basic data appear in Table 2), but simply note that SDSS is certainly capable of finding these stars; indeed, their extremely red colors make them easier to select than the more numerous but anonymously-colored R-type FHLCs that are the focus of this paper. At the conclusion of the Survey, we may expect a modest-sized ($\sim 10^2$) sample of this type of red object.

3. Analysis

3.1. Radial Velocities

The precision of the SDSS in derivation of stellar radial velocities is as yet largely untested. However, two of the stars discussed in this paper, SDSS J171942.4+575838 and 172038.8+575934, are recoveries of previously-known members of the Draco dwarf spheroidal system, and fortuitously have accurately-measured radial velocities in the literature (Olszewski et al. 1995; Armandroff et al. 1995), which can then be used to correct the zero-point of the radial velocities of our new sample. (A third object in common described in §5, Draco C1, is a known radial velocity variable (Olszewski et al. 1995) and thus excluded from this calculation.) The resulting heliocentric velocities (with 1σ uncertainties) are listed in Table 1. Note that the velocity difference between these two Draco stars is measured by the above authors to be -9.2 km s^{-1} and by us as -12.2 km s^{-1}, suggesting that our radial velocity data, or at least this subset thereof, have quite satisfactory *internal* precision. Also, the radial velocity of the Draco symbiotic SDSS J171957.7+575005 (see §5) is given by the above authors as -297 km s^{-1}, while our (corrected) value is -312 ± 13 km s^{-1}. We conclude that the radial velocities shown in Table 1 are accurate to $10 - 15$ km s^{-1}. We anticipate later improvements in this precision as the Survey matures.

Even a casual inspection of the radial velocity results suggests that we are probably observing a mixture of disk and halo populations, as well of course the already-appreciated mix of stellar luminosities. We use these preliminary data to derive some inferences on the underlying populations in §4.3 below. A preview of one surprising result is appropriate here, however: the observed magnitude, proper motion (see §3.2), and radial velocity distribution of our sample indicates that, contrary to all previous FHLC surveys, only a minority of our current stars may be distant giants. Therefore at this early stage of the Survey, we make no attempt to use our radial velocity data for inferences on the dispersion of the outer halo.

3.2. Proper Motions and the Dwarf/Giant Ratio

The SDSS Astrometric Pipeline (Pier et al. 2002) computes J2000 positions for all detected objects, and these positions can be used for a second epoch for measuring proper motions. The accuracies for objects with $r^* < 20$ are set by systematic errors due to short-term atmospheric fluctuations, sometimes referred to as anomalous refraction, as the telescope scans along a great circle. The *rms* errors are less than $\pm 0.\!''1$ in each coordinate. For first-epoch positions, we have taken the position from the USNO-A2.0 catalog (Monet et al. 1998) for the 21 stars that are included in USNO-A. This catalog includes stars detected on *both* the blue and red plates of the first Palomar Observatory Sky Survey (POSS-I). The *rms* errors are approximately $\pm 0''.17$ in each coordinate (Deutsch 1999), or somewhat more for faint stars and stars near plate edges. Because C stars are relatively red, the faint ones are not detected on the POSS-I blue plates, and are not included in USNO-A. For these stars, we have used the unpublished positions measured at the Naval Observatory on all available red survey plates (POSS-I, SERC, ESO/SRC, and POSS-I reject plates)[18]. The errors depend upon the plate(s) on which a star was detected, and on the star's brightness. From the two or more positions and their epochs, the proper motions and their estimated errors are calculated and listed in Table 1. With the typical errors noted above, and with a typical difference in epoch of 46 years, the *rms* errors are about 6 mas yr^{-1} in each coordinate and about 8 mas yr^{-1} in total motion.

We see from the table that 17 objects in the sample show motions significant at the 3σ level, and 26 objects at 2σ significance. We have considered whether the mere detection of proper motion requires the inference of dwarf luminosity; one could, for example, alternatively imagine that both our magnitude and motion limits are sufficiently sensitive that subgiants might be detected. For simplicity we derive crude distances assuming that all dC stars have M_r=10; our observed motions and radial velocities then yield total space velocities which are often high (clearly expected due to selection for detectable proper motion), but *all* well below escape velocity. Although certainly not definitive, we conclude that the evidence is consistent with a dwarf classification for each FHLC with a confidently-detected motion. More quantitative arguments in this regard are given in §4.3.

If we exclude three objects in the Draco dwarf (see §5), the sample numbers 36 objects in total. Green et al. (1992) concluded, based on the first handful of dC stars culled from the heterogenously collected FHLC lists then available, that $> 10\%$ of FHLCs to $V < 18$ must be dwarfs. Given our more homogeneous and, most important, fainter sample, we now see that this value is probably $\geq 50\%$ at $V \leq 20$. The irony that this class of dC objects was totally overlooked until quite recently continues to increase. It has been stated previously by workers in this field (e.g., Green (2000)), but is perhaps still not widely appreciated and thus bears repeating, that despite the focus of more than one century of astronomical spectroscopy, the numerical majority of stars with C_2 in their spectra are dwarfs, not giants.

3.3. Overlap with 2MASS

At least a handful of very cool, dust-enshrouded carbon stars of giant luminosity are known to be located in the distant halo; they were discovered via *JHK* color selection in ground-based

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[18] Many plates were taken for the POSS-I survey and then rejected from the survey for various reasons. Some are of poor quality, but many are of survey quality over most or all of the plate. These plates have all been measured at the Naval Observatory.

near-IR surveys (Cutri et al. 1989; Liebert et al. 2000). Although it is already clear that SDSS will be complementary to this past work, and discover predominantly the more numerous, warmer R-type FHLCs, it is interesting to consider possible overlaps between our FHLC sample and 2MASS sources (Skrutskie et al. 1997). We present results of a search for our objects in 2MASS in Table 2.

Unfortunately at this very early stage of SDSS, and with the entire 2MASS data set not yet accessible, the number of FHLCs which fall within areas containing released 2MASS data is still small, and the list of both detections and non-detections is still clearly limited by small-number statistics. At the moment one sees merely that, not surprisingly, the 2MASS detections tend to be the SDSS objects which are brightest at z, and conversely, that SDSS goes so much fainter than 2MASS for objects with typical FHLC colors that most of our FHLCs will remain too faint for 2MASS. Of the current positive 2MASS detections, about half are dC stars (non-zero SDSS proper motions significant at 3σ), so no obvious luminosity correlation emerges with this very preliminary sample of cross-identifications. Although deeper inferences seem inappropriate until the cross-identified sample (or more probably upper limits thereon) is much larger, it would seem in accordance with expectations from previous work that the two surveys are sampling quite different populations of FHLCs. If one wishes a large sample for halo kinematic work, the SDSS sample will probably ultimately prevail, as the R stars are already known to greatly outnumber the N stars at high latitude. Likewise, as all dC's known to date have R-type spectra, it will almost surely be SDSS that continues to lengthen the list of carbon dwarfs.

4. Discussion

4.1. Luminosity Indicators in FHLCs: Photometric & Spectroscopic

As noted in the introduction, it is imperative that relatively simple observational luminosity discriminants be developed for FHLCs. It has been suspected for a decade that dC stars are substantially more numerous per unit volume than giants. Our current work now shows quantitatively that, at least in the $16 < r < 20$ range, a given FHLC has at least an equal chance of being a dwarf as a giant. As the two types of star differ in luminosity by ~ 10 mag, it is particularly frustrating that discrimination has not proven to be straightforward.

4.1.1. Photometric Luminosity Discriminants

Shortly after the realization that dC stars are in fact a common class of object, Green et al. (1992) discussed the possibility that these objects are often segregated in a JHK color-color diagram from other stars with C spectra. (Indeed, Dearborn et al. (1986) motivated this argument physically when just one object in the class was known.) Later observational work by Joyce (1998) and Totten et al. (2000) provides further encouragement about the utility of this photometric luminosity indicator. On the other hand, current data also clearly show that the IR color segregation is imperfect, and Wing & Jørgensen (1996) and Jørgensen et al. (1998) argue that theoretical model atmospheres for dC stars imply that, at least if T_{eff} is not independently known, JHK colors alone should not be an unambiguous indicator.

Many or most of the new FHLCs here are bright enough to enable future, accurate JHK photometry. Even without awaiting further observations, however, the handful of new dC stars which we report here that fortuitously lie in the released 2MASS data allows us to make at least a cursory reassessment of the situation. Table 2 contains four new dC stars ($\mu > 0$ with $> 3\sigma$ significance) with positive 2MASS detections. In frustrating conformity with the current ambiguous situation, two of these objects (SDSS J073621.3+390725 and 082626.8+470912) exhibit $(H-K),(J-H)$ colors consistent with the (color-segregated) dC's discussed by Green et al. (1992), and two (SDSS J082251.4+461232 and 135333.0−004039) are noticeably inconsistent. It seems clear that JHK photometry is not yet a reliable luminosity discriminant, at least lacking further ancillary clues.

4.1.2. Spectroscopic Luminosity Discriminants

We have already noted that at low to moderate spectral resolution, giant and dwarf FHLCs have very similar spectra. Presumably at high resolution, there will be various unambiguous discriminants available. However, these are by definition faint objects, and it would be very useful to recognize spectroscopic luminosity discriminants accessible to modest-sized telescopes. On the basis of the spectra of the first few, brighter dC's, Green et al. (1992) suggested that the appearance of a strong, sharp C_2 bandhead at λ6191, probably due to the $\Delta v = -2$ bands of $^{13}C^{12}C$ and $^{13}C^{13}C$, might be such a diagnostic for dwarfs. On the other hand, at least a few contrary examples, where AGB stars show the feature prominently, are already known (Gordon 1971; Meusiner & Brunzendorf 2001), so this indicator is clearly not perfectly reliable.

Our new, spectrally homogeneous sample of FHLCs has been used to reexamine the issue of the λ6191 band, and the results are encouraging. Most of the objects with significant detections of proper motion and good quality spectra do show the band, sometimes very prominently. For example, even at the modest scale of Figure 1, the feature is easily visible in SDSS J090011.4-003606, and most especially SDSS J012150.3+011303 (in fact our highest proper motion object), where it is very strong. Conversely, most of the good quality spectra of objects with no confident detection of motion lack the λ6191 band. However, a few of the reddest, coolest (as judged by NaD line strength) FHLCs with positive motion detections and good quality spectra still lack the λ6191 band, perhaps implying that the feature may be temperature- as well as luminosity-sensitive. This conclusion, while annoying if correct, still detracts little from the utility of the feature as a luminosity indicator; it merely implies that lack of λ6191 in a cooler FHLC is inconclusive regarding the luminosity. Luckily we are able to suggest below a different indicator for the cooler subset of FHLCs.

As pointed out in §2.2.2, a small fraction of our objects show Balmer emission. As dC stars presumably are unlikely to possess active chromospheres or coronae, or undergo current mass loss, one might look to this feature as a designator of giant luminosity (especially as the presumptive binary companion that donated the C is normally invisible in the spectrum). Unfortunately, we already know of contrary cases: the dC PG0824+289 shows Balmer emission (Heber et al. 1993), presumably due to heating of the dwarf by the very close hot DA companion which is also visible in the spectrum. We draw attention to a second possible case in this class in §5 below.

Several of our better exposed spectra show prominent BaII $\lambda\lambda$6130, 6497 absorption (the latter normally blended with Ti, Fe, and Ca); an example is given in Figure 5. Although normally prominent in supergiants, Ba is known to be enhanced in dC stars as well (Green & Margon 1994). Therefore although this is an astrophysically interesting feature, it probably will not be a reliable luminosity indicator.

An interesting feature of some of our spectra is the presence of very prominent CaH $\lambda\lambda$6382, 6750 bands in the cooler FHLCs, i.e., those with strong NaD and redder colors. Again a good example is shown in Figure 5. Although we are not aware of any previous discussion of this feature in C stars, in K and M stars CaH is normally strong only in dwarfs, peaking at late K (e.g., Kirkpatrick et al. (1991)). We propose that for this cooler subset of FHLCs, CaH may be an effective low resolution luminosity indicator – in our sample, only stars with positive motion detections show the bands. Serendipitously, this feature appears at temperatures which are apparently too cool for the λ6191 $^{13}C^{12}C$, $^{13}C^{13}C$ band discussed above, and is thus nicely complementary.

Despite the size of our current sample as compared with previous work, when subdivided by temperature and proper motion, the number of FHLCs with high quality spectra is still quite modest. We defer until a subsequent paper, where it is already evident that the sample size will more than double, more quantitative discussions of the luminosity and temperature correlation of spectral features. Ultimately photometric variability may prove a simple luminosity discriminant, although the absence of same will remain inconclusive. While a few isolated measures which show variability could still be due to interactions in the rare very close binary dC's such as PG0824+289, consistent, chaotic variability is probably associated only with mass loss in the giant FHLCs.

4.2. Surface Density of FHLCs

As discussed briefly in §2.1, our current sample of 39 carbon stars should not be considered "complete" for several reasons. Most importantly, SDSS galaxies and quasar candidates are targeted for follow-up 2.5m spectroscopy at higher priority than the bulk of the carbon star candidates. In some regions of the survey, the surface density of galaxies and QSO candidates is so high as to effectively consume nearly all available spectroscopic fibers. On average, in the early commissioning phases of the survey, about 40% of the requested carbon star candidates received spectroscopic fibers, but even this average number changed as spectroscopic target selection algorithms for various other object classes were refined during SDSS commissioning. On the other hand, some of the carbon stars discussed in this paper are fainter than the typical $r < 19.5$ limit imposed for 2.5m spectroscopy for the bulk of SDSS carbon star candidates. Aside from their magnitudes, these fainter discoveries do generally meet the same color-selection criteria for other carbon star candidates (as may be discerned from Figure 2), but in fact were selected for spectra by the algorithms aimed at high redshift quasar candidates (for which the magnitude limit is somewhat fainter).

We may therefore only quote a conservative lower limit on the number density of confirmed carbon stars (with $r > 15$; the SDSS spectroscopic bright limit), from the following considerations. The region surveyed spectroscopically with the SDSS 2.5m, at the time of compilation of the current sample, is of order 700 deg^2. In that region, SDSS found at least 35 confirmed carbon stars; we conservatively exclude from this count the 3 carbon stars in Draco and the 1 object spectroscopically confirmed from the ARC 3.5m. Thus the surface density of FHLCs is $>$0.05 deg^{-2}. This number differs little from the value reported by the recent Hamburg/ESO Survey for FHLCs (Christlieb et al. 2001), despite the fact that SDSS clearly can reach objects 3 mag fainter. This is a striking and surprising result, but it is much too early in our survey to attempt to attach any physical significance to this issue: incompleteness of SDSS selection is at least as likely an explanation as any genuine flattening in the faint end of the luminosity function. Regardless of these current ambiguities, it is clear that SDSS will discover and spectroscopically confirm several hundred, and perhaps a few thousand, FHLCs in the full survey. Far more quantitative limits on FHLC surface density will therefore become available when a substantial volume of SDSS production data are on hand. At the time of submission of this paper, an additional 100 FHLCs have been identified, but not yet examined in detail.

4.3. Some Comments on Population Issues

The FHLCs selected from the APM survey (Totten & Irwin 1998; Ibata et al. 2001) are cool AGB stars at distances of tens of kpc. The stars found in this work, however, are primarily warmer and fainter. Both differences could result in different mixes of giant and dwarf stars, or of halo and disk stars, in our sample. In order to place some constraints on the population of stars in our sample, we have constructed simple Monte-Carlo models of possible FHLC populations, to ascertain which models are consistent with the observed sample and which are not. These models are not exhaustive and will be developed more thoroughly in the future as the sample size increases.

4.3.1. Models

The Monte Carlo program places stars around the Sun based on an assumed space density (with an exponential scale height for disk stars and a galactocentric radial power law for halo stars), with absolute magnitudes drawn from an input luminosity function (LF), and with UVW space velocity components drawn from an input distribution of a gaussian velocity ellipsoid with specified UVW dispersions and Galactic rotation velocity. Then, for stars not in the Galactic plane with apparent magnitudes within a specified range ($15.0 < r^* < 19.5$), the observables (proper motion, radial velocity, and apparent magnitude) including observational errors appropriate for SDSS data are calculated and are entered in the model sample.

The program requires values for the velocity ellipsoid and the LF. The input LF used for giant C stars has a maximum per unit magnitude at $-3.5 < M_r < -2.5$, with progressively fewer stars at $-4.5 < M_r < -1.5$. This LF is fainter than the typical $M_R \sim -3.5$ expected for stars in the APM survey (Totten et al. 2000), but is consistent with the warmer colors of stars in our sample (see their Figure 4). The LF used for all dwarfs has a maximum at $9 < M_r < 10$, with progressively fewer stars at $7 < M_r < 12$. This is consistent with the three dwarf C stars with measured parallaxes, all of which have $M_r \sim 9.3$ (Harris et al. 1998). Values for the velocity ellipsoid are taken from Reid et al. (1995) for the disk, and from Chiba & Beers (2000) for the halo and thick disk. A scale height of 250 pc is used for the disk, and 1000 pc for the thick disk.

4.3.2. Results of Modeling

The models make predictions for the distributions of apparent magnitude, radial velocity, and proper motion that can be compared with the observed distributions. The three known extragalactic stars (members of the Draco dwarf) are excluded from the comparison, as well as two other objects where radial velocity data were not available at the time of the analysis, or where uncertainties were abnormally large due to reduction problems, leaving the final comparison sample at 34 objects.

The results are shown in Figure 6, where the top figures show several illustrative models, and the bottom figures show a model with three components that is consistent with all the data. The apparent magnitudes are shown in panel (a). The falling curve predicted for halo giant stars is due to the space density of halo stars dropping steeply in the outer halo. (A density $\propto r^{-3.5}$ is often accepted for the Galaxy.) Panel (a) indicates that most stars in the sample are probably dwarfs, and that the fraction of dwarfs is likely to be rising toward fainter magnitudes. This result is completely opposite from the conclusion of Totten et al. (2000) on the dwarf/giant ratio in the APM survey of FHLCs. The APM survey, however, is made up of much redder and (especially) brighter stars with a magnitude distribution dropping toward fainter magnitudes – it has only two objects with $R > 16$, whereas our sample has essentially all stars of $r^* > 16$ – so the markedly different conclusions are perhaps not unexpected.

The distribution of radial velocities is shown in panel (b). The middle panels indicate that about two thirds of the sample is a halo population, either dwarf or giant stars. This substantial fraction of disk dwarf stars is larger than for the halo-dominated dwarf carbon stars already known, but the difference is not unexpected given that the selection is not kinematically biased.

The distribution of proper motions depends on the distances of the stars, and their inferred distances depend on the assumed luminosity. Because the luminosity function of dwarf carbon stars is unknown, different proper motion distributions can be fit by adjusting the assumed LF. Choosing the LF to fit the data is, in essence, finding the statistical parallax that makes the radial velocity and proper motion distributions mutually consistent. Panel (c) shows results, using a single LF (see below) for all dwarfs. It is possible that disk and halo dwarf carbon stars have different LFs. The fit to the observed distribution would be improved if the disk dwarfs have lower luminosities than the halo dwarfs. The LF for giant stars is better known, and it has little impact because the proper motions are small in any case.

The lower panels compare our sample data (excluding the three stars in Draco that are not representative of the Galactic halo) with a simple population model with three components that fits the data fairly well: 15% halo giants, 50% halo dwarfs, and 35% disk dwarfs. Other combinations are also consistent with the data within limits; e.g. disk stars can be replaced with thick disk stars, and the proportion of halo and disk dwarfs and their luminosities can be changed in tandem. The conclusion is inescapable, however, that the dC stars are commonly found in both halo and disk populations. This conclusion has been anticipated on general stellar evolution grounds (deKool & Green 1995), but the previous small, heterogeneous samples of dC's have yielded scant empirical evidence in this regard.

For the stars in our sample with statistically significant proper motions, the reduced proper motions are in the $14 < H_r < 19$ range, and upper limits for the stars without significant motions range from $H_r < 13$ through $H_r < 16$. These results are also consistent with a mixture of halo dwarfs, disk dwarfs, and giants, but a larger sample will be needed to make more cogent comments.

Our models imply that whatever giant stars exist in our sample must (not surprisingly) have insignificant proper motion, and most should be bright with large radial velocity. (Note that the three giants in Draco do match these expectations.) The best candidate on these simplisitic grounds is SDSS J114125.8+010504, whose blue colors and spectrum do in fact strongly imply it is a giant (see §5). Other less likely candidates are SDSS J095516.4+012130, J221854.3+010026, J144150.9-002424, J075116.4+391201, and J015232.3-004933. Indeed, probably only a handful of the current sample are giants. For some time it has been realized that there must be some threshold sensitivity where dC stars become more the norm rather than a rare curiosity amongst carbon stars: it appears that the SDSS has crossed this threshold.

One concern about this discussion is that the sample may be biased toward one population or another by selection effects that are not included in the models. In this initial paper, some biases undoubtedly exist toward some spectral types, temperatures, and atmospheric compositions that we do not yet understand. We know of no reason why selection of dwarfs should be favored over giants, for example. It is plausible, however, that warm metal-poor dwarfs may be favored over warm metal-rich dwarfs, creating a higher halo/disk ratio in the sample than really exists in the solar neighborhood. Future work with a larger sample should help to address these issues.

5. Comments on Individual Objects

SDSS J003813.2+134551. $H\alpha$ in emission.

SDSS J012150.3+011303. This star has by a considerable margin the largest proper motion in our sample ($0\farcs24$ yr^{-1}), and amongst the largest of any dC yet reported (cf. Deutsch (1994)). At this magnitude ($r^* = 17.0$) in the northern sky, it would be surprising if it had not already been noted on the grounds of motion alone. This proves indeed to be the case; it is one of the few previously-cataloged objects in our sample. The object is identical to LP587-45, but has a confusing and unfortunately erroneous literature trail which we attempt to unsnarl here. LP587-45 was proper motion selected by Luyten (1979a) in the NLTT catalog, where photographic magnitudes and proper motion data are in excellent agreement with our results. (The precise agreement of the motion and position angle make the cross-identification unambiguous.) The NLTT lists the color class as "*m*" (essentially simply "red"), and to our knowledge there has been no previously reported spectrum, and thus recognition of the unusual dC status. Unfortunately, Luyten (1979b) designates this star as the visual companion of the far-more famous LP587-44 (Luyten 1980) (= WD0119-004, = GR516), a very-well studied bright DB star with numerous literature citations. This attribution is in error; LP587-45 and LP587-44 have essentially the identical right ascensions, but differ in declination by $\sim 1.5°$. Inspection of the POSS indicates that the DB star does indeed have a faint companion of $9''$ separation at *p.a.* = 264° as recorded by Luyten (1980), but this companion should be designated as anonymous, or LP587-44B, not the (now recognized) dC star LP587-45, an entirely unrelated object in a different part of the sky.

SDSS J013007.1+002635. One of the few objects with strong, narrow $H\alpha$ emission, and one of the coolest in the sample (very strong NaD); more important, this star has a composite spectrum. The object is probably a dwarf, with a 2.3σ detection of proper motion. In addition to the Swan and red CN bands, there are multiple broad Balmer absorptions in the blue. We are aware of only two previously-reported dC stars with composite spectra (Heber et al. 1993; Liebert et al. 1994). However, the situation here is complex; the SDSS images show a fainter, blue companion located $4\farcs5$ WNW. It is possible this object contaminates the spectrum of the FHLC. On the other hand, the photometry from the imaging data base, where the two objects should be well-separated, shows the FHLC to be far more ultraviolet than any other object in the sample, perhaps suggesting that the Balmer and C_2 features do indeed originate from the same image. Further observations are clearly needed.

SDSS J033704.0-001603. Strong $H\alpha, H\beta$ emission.

SDSS J085853.3+012243. Contradictory diagnostics: strong $H\alpha, H\beta, H\gamma$ emission; very prominent NaD, CaH absorption. Significant proper motion detection and thus a rare dC with emission, perhaps indicating an unseen but hot, irradiating companion. Yet the observed $(g^* - r^*) = 2$ is the reddest object in the sample.

SDSS J112801.7+004035. Note extremely high radial velocity; surely a candidate extragalactic object, e.g., a member or ex-member of a dwarf spheroidal in the Local Group. Colors and spectrum are normal.

SDSS J114125.8+010504. Stands out as the bluest object in the sample in $(g^* - r^*)$, and very red in $(i^* - z^*)$. Spectrum of a classical CH star, similar to HD 5223 (see Barnbaum et al. (1996)). High radial velocity and lack of proper motion perhaps suggest halo giant system.

SDSS J132840.7+002717. Noisy spectrum: classification may be uncertain.

SDSS J171942.4+575838. Previously known C star in the Draco dwarf galaxy (=BASV 461, =Draco 461); see Baade & Swope (1961) and Armandroff et al. (1995).

SDSS J171957.7+575005. Previously known, highly unusual emission line object in the Draco dwarf galaxy (= Draco C1). First reported by Aaronson et al. (1982), further remarks by Munari (1991), Armandroff et al. (1995) and Olszewski et al. (1995). It is generally classified as a symbiotic carbon star, of which fewer than a handful are known both in the Galaxy and Local Group combined. Although the prototype, UV Aur, has been studied for some time (Sanford 1949), objects like this one with excitation as high as indicated by the very strong HeII λ4686 emission are almost unknown; the other examples such as SS 38 (Schulte-Ladbeck et al. 1988) and UKS Ce-1 (Longmore & Allen 1977) are hardly household words. Although previously detected in X-rays (Bickert et al. 1996; Mürset et al. 1996), our automated pipeline processing system also drew attention to the coincidence with a ROSAT X-ray source, indicating that new stellar X-ray source optical identifications will be made by SDSS. Our spectrum is of greater resolution, wavelength coverage, and signal-to-noise ratio than previously published spectra; in an effort to stimulate further interest in this extraordinary star, we display the spectrum of Figure 1 at a greatly enlarged scale in Figure 7, truncating the strong Hα emission so that other features are readily visible. Excess blue flux in our photometry, possibly due to the continuum of the companion.

SDSS J172038.8+575934. Previously known C star in the Draco dwarf galaxy (=BASV 578, =Draco C4); see Baade & Swope (1961), Armandroff et al. (1995) and Olszewski et al. (1995).

SDSS J172909.1+594035. Extreme colors: the bluest $(u^* - g^*)$ and $(i^* - z^*)$ of the sample (see Table 1, Figure 2), but very faint, and the uncertainties on the measured magnitudes are large. Although located $\sim 2.4°$ from the center of the Draco dwarf, whose tidal radius is only $\sim 0.65°$ (Odenkirchen et al. 2001), it has the correct radial velocity for membership. If a member, the implied luminosity is low compared with the other known Draco C giants, but the object could be a CH star, and the (quite noisy) spectrum does not contradict this possibility. The issue of possible tidal debris far from Draco has recently been considered by Piatek et al. (2001) and Odenkirchen et al. (2001), who find no candidate (ex-)members nearly this distant, although they search for macroscopic overdensities and color sequences, rather than individual stars; and those Draco candidate members that are found relatively distant from the core are near the major axis, contrary to this object. Certainly other Local Group dwarfs such as the Sagittarius dSph are known to have debris many degrees distant (Newberg et al. (2002) and references therein), so an asssociation here may still be plausible and important.

6. Conclusions

Despite their rarity and the relatively benign colors of the majority of the objects, large numbers of FHLCs can be efficiently selected by the SDSS. The current sample, although small compared with the ultimate end product of the Survey, already provides interesting information on a variety of FHLC issues. At the completion of the Survey, the homogeneously selected FHLC sample will for the first time be sufficiently large that statistics are no longer dominated simply by the size of the catalog, though a negligible fraction of SDSS resources are applied to this problem.

The SDSS has already fulfilled the previously undemonstrated expectations that a sufficiently sensitive and efficient selection technique for FHLCs would yield the (formerly) exotic dwarf carbon stars in copious numbers. For the first time we constrain the ratio of carbon dwarfs to giants in the $16 < r^* < 20$ range: it is at least near to unity, and possibly considerably larger. Preliminary kinematic analyses imply that there are distinct halo and disk dwarf populations.

Lacking the positive detection of proper motion, separation of the dwarfs from giants for FHLCs remains problematic. We find no single photometric or (low resolution) spectroscopic diagnostic that applies to all objects, but suggest the addition of one further weapon to the arsenal: in sufficiently cool FHLCs, the presence of strong CaH bands is an effective dwarf indicator.

Numerous unusual FHLCs have also been identified for further study.

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Table 1. Faint High Latitude Carbon Stars Discovered in SDSS Commissioning Data

Object Name[a] SDSS J+	r^*	$(u^* - g^*)$	$(g^* - r^*)$	$(r^* - i^*)$	$(i^* - z^*)$	μ (mas yr^{-1})	p.a. °	RV (km s^{-1})
003013.1−003227	19.49	2.84	1.87	0.50	0.24	11(9)	...	46.3(8.3)
003813.2+134551	19.32	2.22	1.60	0.50	0.31	5(12)	...	−10.0(11.3)
003937.3+152911	18.61	1.67	1.05	0.30	0.17	31(8)	174	−130.1(17.1)
012150.3+011303	17.02	2.71	1.69	0.50	0.14	241(8)	124	−18.3(7.7)
012526.7+000449	19.34	1.42	1.63	0.54	0.16	56(12)	101	−49.1(17.3)
013007.1+002635	17.62	0.40	1.01	0.43	0.36	28(12)	135	−16.2(9.4)
015232.3−004933	18.28	3.22	1.56	0.57	0.29	19(8)	...	−31.2(11.3)
023208.6+003639	19.46	2.00	1.59	0.56	0.27	34(12)	130	9.6 (21.2)
025634.6−084854	19.47	1.94	1.10	0.25	0.17	43(12)	143	−121.0(12.0)
033704.0−001603	18.67	2.38	1.92	0.71	0.30	11(8)	...	−25.4(12.0)[b]
073621.3+390725	18.43	3.21	1.52	0.49	0.16	58(8)	234	−28.7(11.3)
075116.4+391201	17.61	3.47	1.60	0.58	0.43	7(8)	...	−15.3(9.9)
075953.6+434021	19.48	3.64	1.91	0.63	0.13	6(10)	...	6.3(26.6)
082251.4+461232	17.22	2.79	1.40	0.77	0.22	25(8)	219	47.7(8.0)
082626.8+470912	17.77	2.80	1.44	0.48	0.31	41(8)	143	49.4(6.6)
085853.3+012243	18.31	2.46	1.99	0.67	0.36	29(8)	130	89.8(16.2)
090011.4−003606	18.44	3.29	1.47	0.47	0.26	59(8)	3	227.1(12.5)
094858.7+583020	18.77	2.55	1.15	0.33	0.22	24(8)	176	−29.8(42.0)
095516.4+012130	18.35	2.85	1.60	0.52	0.26	19(8)	...	154.3(15.4)
100432.5+004338	19.99	1.64	1.71	0.56	0.19	36(12)	174	167.4(17.9)
112801.7+004035	18.81	2.44	1.41	0.38	0.23	22(10)	...	562.1(23.3)
112950.4+003345	18.28	2.26	1.40	0.41	0.33	44(10)	236	35.8(10.8)
114125.8+010504	17.29	2.12	0.89	0.15	0.29	4(8)	...	119.8(10.8)
114731.7+003724	18.60	1.70	1.05	0.23	0.13	34(8)	179	43.3(5.2)
115925.7−031452	18.76	1.78	1.08	0.17	0.10	23(10)	...	...[c]
132840.7+002717	19.40	1.88	1.17	0.18	0.18	47(16)	165	117.7(11.0)
135333.0−004039	16.60	2.68	1.59	0.53	0.27	65(8)	235	−32.1(13.8)
142112.4−004823	19.05	2.13	1.51	0.36	0.42	23(7)	105	−85.0(9.0)
144150.9−002424	17.86	2.56	1.72	0.66	0.26	8(8)	...	−44.8(14.4)
153732.2+004343	17.63	2.54	1.82	0.63	0.38	36(8)	155	56.4(8.4)
161657.6−010350	19.06	2.70	1.70	0.60	0.22	25(10)	215	−46.3(11.4)
171942.4+575838	16.81	3.29	1.18	0.33	0.34	19(8)	...	−301.4(13.1)
171957.7+575005	16.47	1.25	1.25	0.28	0.41	5(8)	...	−311.7(13.5)
172038.8+575934	17.76	2.65	1.17	0.29	0.23	6(8)	...	−289.2(10.3)
172909.1+594035	20.19	0.12	1.84	0.44	−0.09	...[d]	...	−281.9(16.7)
173650.5+563801	19.19	2.27	1.72	0.67	0.32	18(12)	...	−19.2(10.5)
221450.9+011250	19.85	1.86	1.54	0.55	0.11	34(15)	219	−191.7(19.0)
221854.3+010026	19.24	1.78	1.09	0.37	0.15	18(12)	...	−307.2(10.2)
230255.0+005904	17.71	2.30	1.45	0.52	0.31	46(8)	236	−34.6(13.1)

General notes: Parenthesized values are $\pm 1\sigma$ uncertainties. See §5 for specific notes on individual objects. Radial velocities are heliocentric.

[a] Naming convention is equinox 2000, *hhmmss.s*, ±*ddmmss*. Epochs vary slightly, but all lie in the 1999.5 ± 1.0 interval.

[b] Two separate observations exist; weighted average RV is quoted.

[c] ARC 3.5m spectrum only; no RV data available.

[d] Object very faint; no suitable first epoch data for quantitative proper motion analysis, although informal indications are that any motion must be small.

Table 2. SDSS Faint High Latitude Carbon Stars in Released 2MASS Fields

SDSS J+	2MASS+[a]	z^*	J	H	K
003013.1−003227	...	18.75	...	...	...
003813.2+134551	...	18.51	...	...	...
003937.3+152911	...	18.14	...	...	...
012526.7+000449	...	18.64	...	...	...
025634.6−084854	...	19.03	...	...	...
033704.0−001603	0337040−001602	17.66	16.25(0.09)	15.47(0.09)	15.15(0.14)
073621.3+390725	0736213+390725	18.10	16.55(0.13)	16.04(0.20)	15.60(0.22)
075116.4+391201	0751163+391201	17.46	15.18(0.06)	14.40(0.06)	14.10(0.07)
075953.6+434021	...	19.03	...	...	...
082251.4+461232	0822514+461231	16.68	15.50(0.07)	14.6 (0.08)	14.49(0.07)
082626.8+470912	0828267+470911	17.59	15.96(0.10)	15.22(0.11)	>14.61
090011.4−003606	...[b]	17.71	...	...	...
115925.7−031452	...	18.49	...	...	...
122740.0−002751[c]	1227400−002751	15.08	12.76(0.03)	11.50(0.02)	10.55(0.03)
135333.0−004039	1353330−004039	16.34	14.59(0.04)	13.80(0.04)	13.61(0.05)
144150.9−002424	1441509−002424	17.46	15.50(0.07)	14.67(0.07)	14.22(0.08)
144631.1−005500[c]	1446311−005500	14.96	12.38(0.03)	11.53(0.03)	11.05(0.03)

General notes: Parenthesized values are $\pm 1\sigma$ uncertainties. z^* magnitudes from SDSS; JHK magnitudes from 2MASS Second Incremental Release Point Source Catalog. Note that the former system is AB-based, and the latter, Vega-based.

[a] Blank entry indicates object lies within 2MASS survey area, but was not detected by 2MASS.

[b] Faintly visible on sky image gifs, but not cataloged by 2MASS.

[c] Not part of autonomously selected sample, but included here for completeness: see §2.2.2.

Fig. 1.— Spectra of 39 high-latitude carbon stars observed by SDSS. With the exception of 115925.7-031452, all data were obtained with the SDSS 2.5 m telescope and spectrographs; the latter was observed by the APO 3.5 m telescope. The spectra are sky-subtracted and flux-calibrated using observations of standard early F stars. The results of imperfect sky subtraction are seen at 5577 Å and at wavelengths > 8500 Å in many of the spectra. The data are binned to a resolution of about 5 Å for the brighter stars and 10–20 Å for the fainter objects.

Fig. 2.— Color-color diagrams of the 39 SDSS FHLCs, as well as SDSS photometry of $\sim 14,0000$ anonymous field stars with $r^* < 17$ (Finlator et al. 2000), displayed to illustrate the normal stellar locus. The new objects are displaced from the normal locus in the direction and amount predicted by Krisciunas et al. (1998) on the basis of observations of previously known FHLCs, but the relatively small degree of segregation demonstrates that the photometry must be both precise and homogeneous to discover FHLCs with high efficiency. *Open symbols:* carbon stars with $\mu > 30$ mas yr^{-1}, and thus newly recognized dwarfs; *filled symbols:* stars with proper motions in SDSS data of $\mu < 30$ mas yr^{-1}, and thus probably a mixture of giants and dwarfs. Clearly SDSS colors do not provide effective luminosity discriminants. A few objects with unusual colors are discussed in §5.

Fig. 3.— Finding charts for the 39 faint high latitude carbon stars observed in SDSS commissioning data. All frames are i-band images taken with the SDSS camera, and are $100''$ on a side. The small arrow in the lower left of each chart indicates the direction of north; all charts have "sky" parity, so east is located 90° counterclockwise from the north arrow.

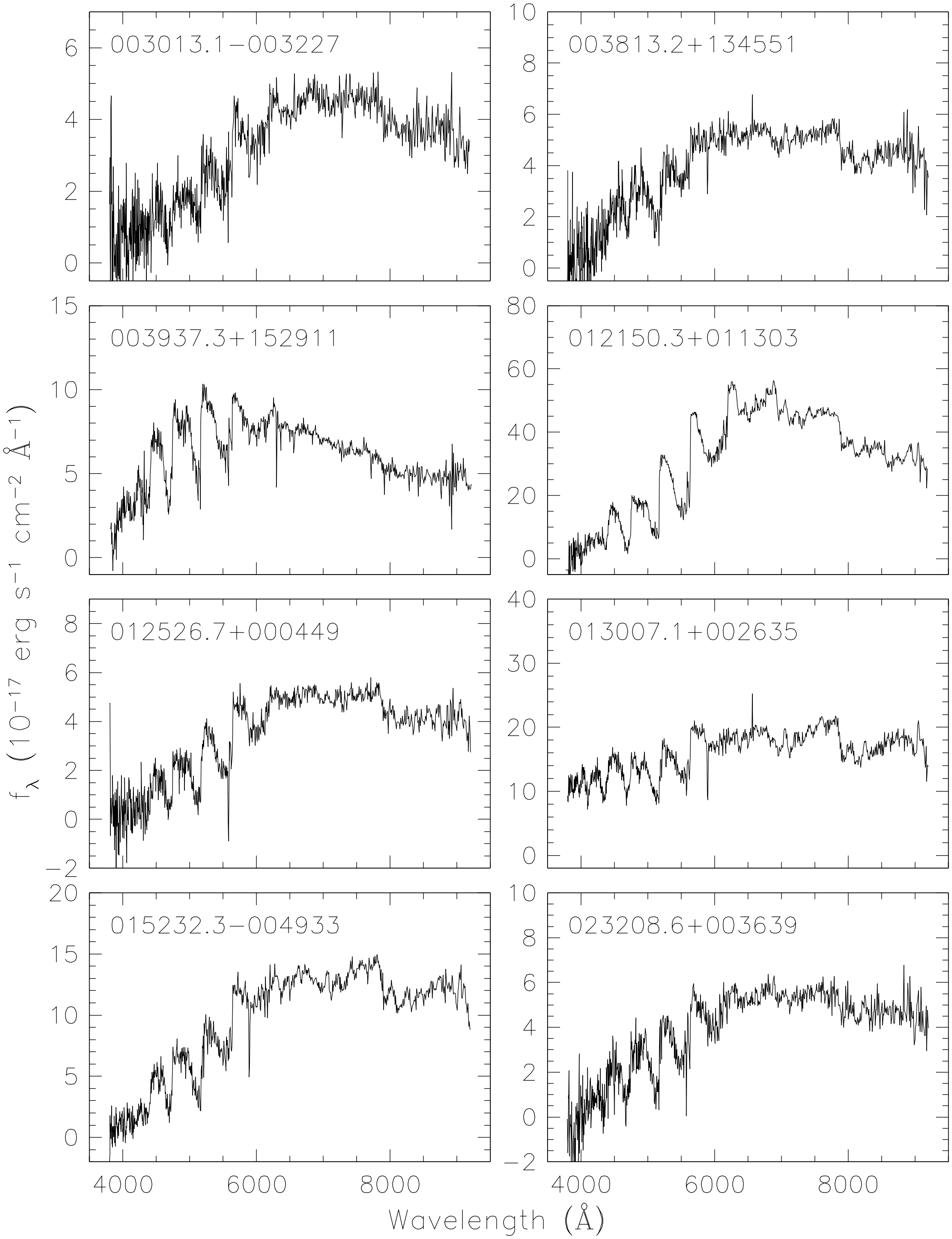
Fig. 4.— ESO NTT spectra of two very red FHLCs found in SDSS data. These spectra, obtained in April 2001, are of spectral resolution $R \sim 270$ (*lower panel*) and $R \sim 600$ (*upper panel*). These are probably the rarer, N-type (giant) FHLCs discussed by Totten & Irwin (1998) rather than the R-type objects copiously found in our survey; note the $H\alpha$ emission in the brighter object. Unlike SDSS spectra, the telluric bands are not removed in these reductions; the A and B bands are particularly prominent. The absolute flux calibration is uncertain outside of the $\lambda\lambda 5300 - 9300$ range.

Fig. 5.— Many of the new FHLCs are bright enough that the SDSS spectra are useful for astrophysical issues, as opposed to simply classification. Shown here is a portion of the spectrum of SDSS J153732.2+004343, a previously uncataloged $r^* \sim 17.6$ object with strong C_2 Swan bands (not shown in this segment) and a high proper motion, indicating a new dwarf C star. The complete spectrum of this object appears in Figure 1. Note the very strong NaD absorption: this is one of the cooler FHLCs in our sample. The CaH bands are this strong only in dwarfs, and thus we suggest that in this cooler subset of the FHLCs, these bands can serve as the long-sought low-resolution spectroscopic luminosity discriminant, eliminating the need for proper motion data. Note also the strong BaII.

Fig. 6.— Results of Monte Carlo models which vary dwarf versus giant and disk versus halo fraction

of FHLCs, compared with the observed magnitude (*panel 'a'*), radial velocity (*panel 'b'*), and proper motion (*panel 'c'*) characteristics of the sample (excluding three known extragalactic objects). In each case, the upper panel is the model, and the lower panel illustrates one case which fits the data well: 15% halo giants, 50% halo dwarfs, and 35% disk dwarfs.

Fig. 7.— The spectrum of SDSS J171957.7+575005, a symbiotic carbon star in the Draco dwarf galaxy, also known as Draco C1. In addition to the C_2 Swan and CN bands, note the strong Balmer and HeI $\lambda\lambda$ 5876, 6678, 7065 emission, and most especially the extraordinary HeII λ4686 strength (HeII$\sim$Hβ). The intense $H\alpha$ emission is truncated for convenience in scaling, but the peak intensity is 700 units.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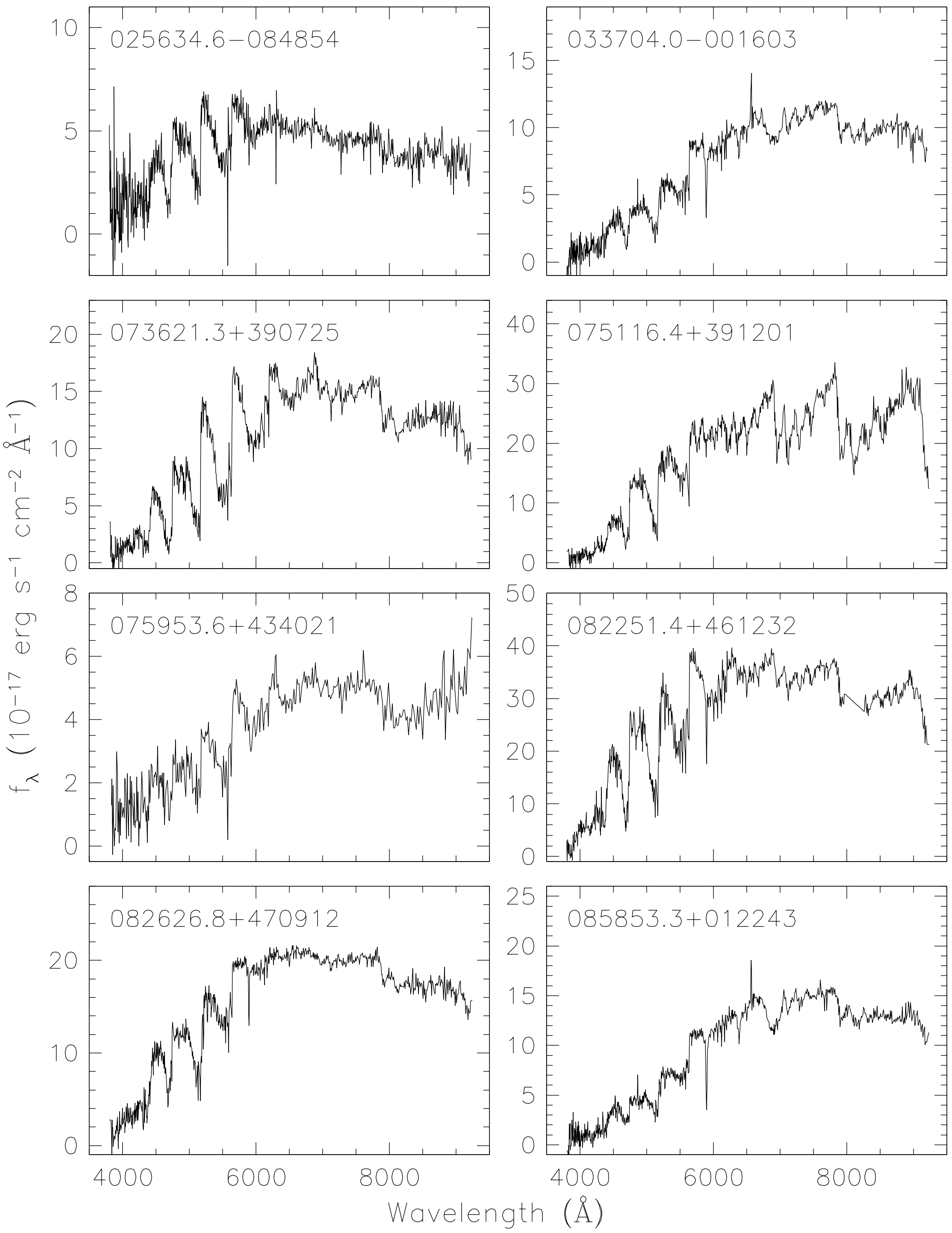
003813.2+134551
003937.3+152911
012150.3+011303
012526.7+000449
013007.1+002635
015232.3−004933
023208.6+003639
f_λ (10^{-17} erg s^{-1} cm^{-2} Å^{-1})
Wavelength (Å)
4000
6000
8000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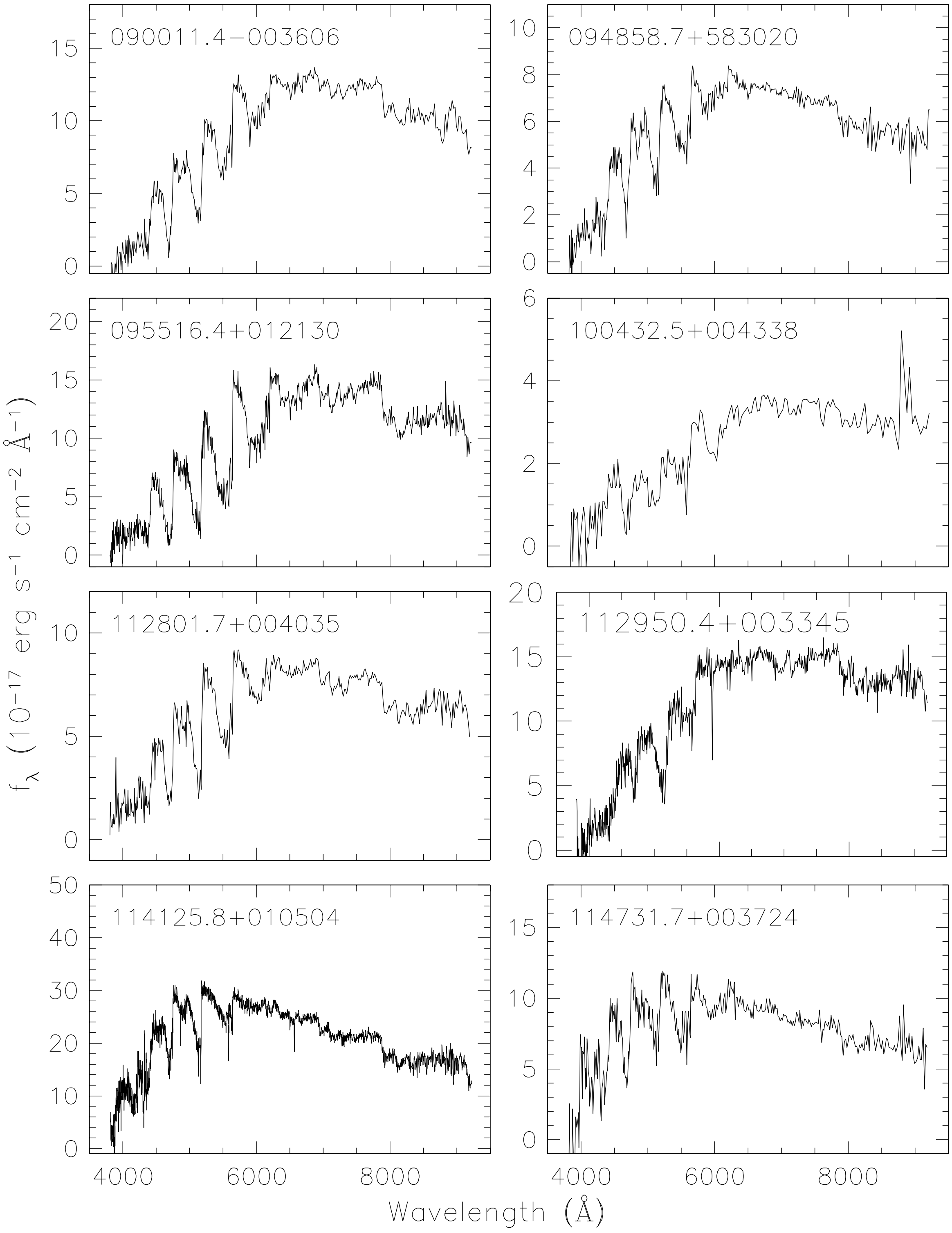
033704.0−001603
073621.3+390725
075116.4+391201
075953.6+434021
082251.4+461232
082626.8+470912
085853.3+012243
f_λ (10^{-17} erg s^{-1} cm^{-2} Å^{-1})
Wavelength (Å)
4000
6000
8000
0
5
10
15
20
25
30
40
50
2
4
6
8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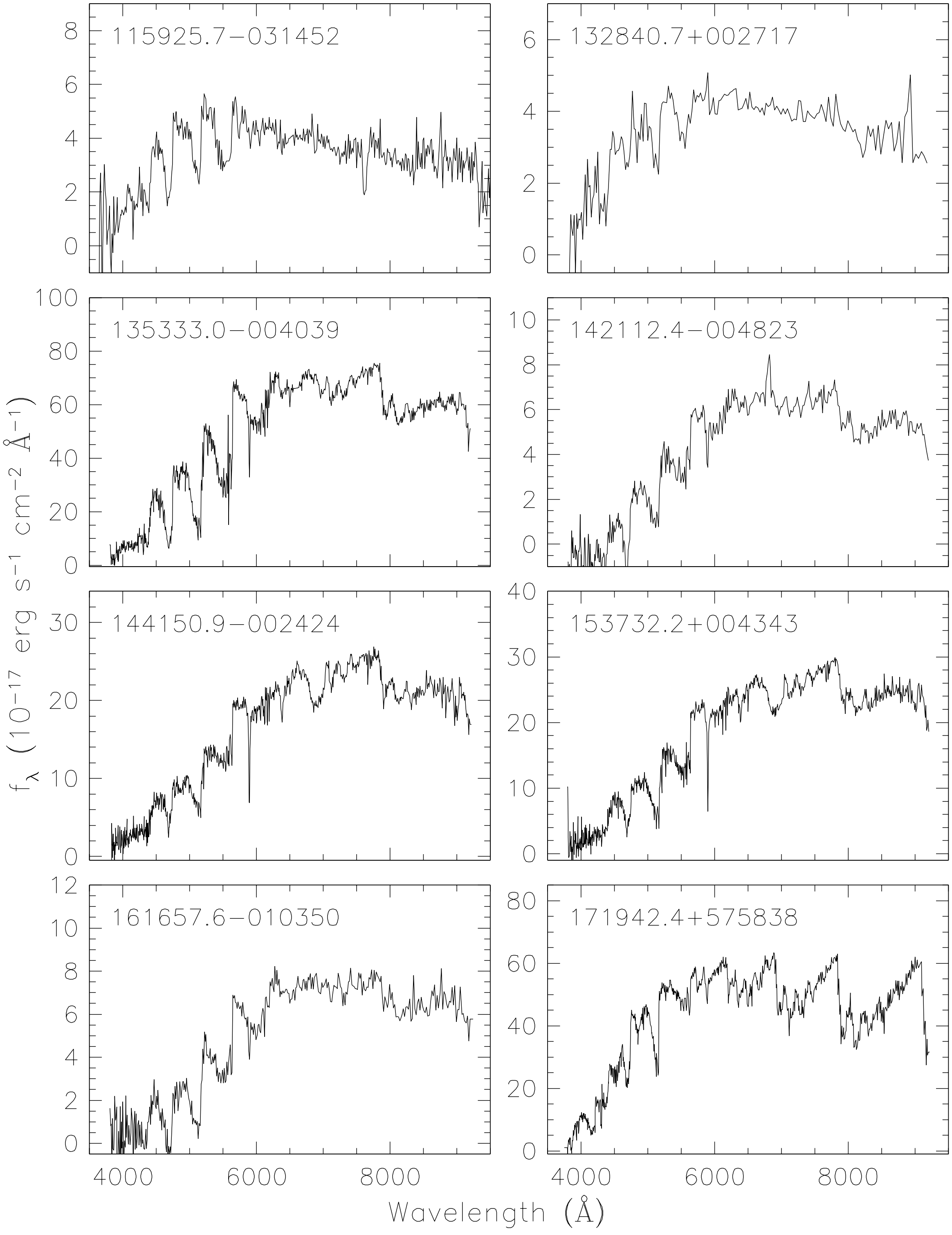
094858.7+583020
095516.4+012130
100432.5+004338
112801.7+004035
112950.4+003345
114125.8+010504
114731.7+003724
f_λ (10^{-17} erg s^{-1} cm^{-2} Å^{-1})
Wavelength (Å)
4000
6000
8000
0
5
10
15
20
2
4
6
8
30
40
50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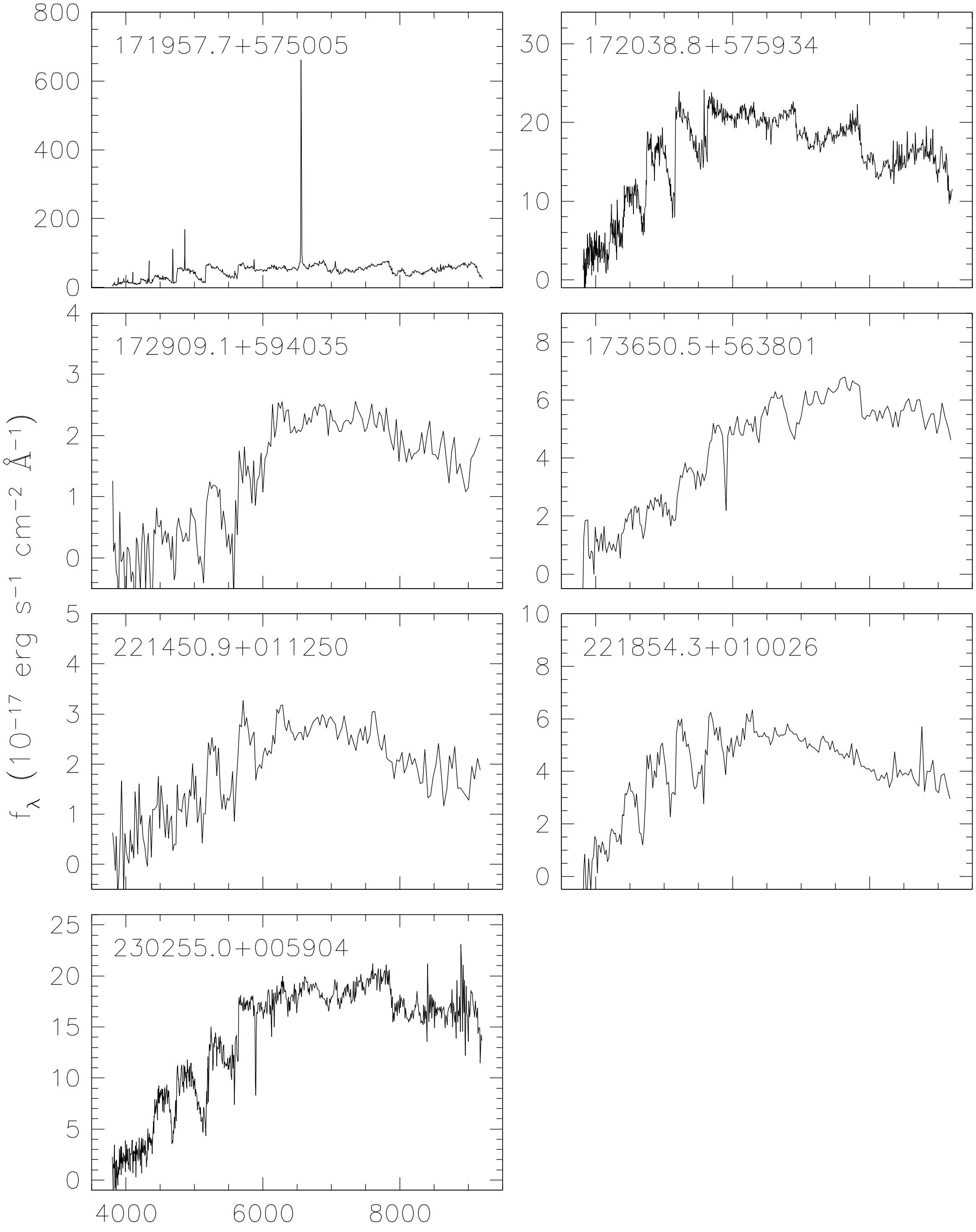
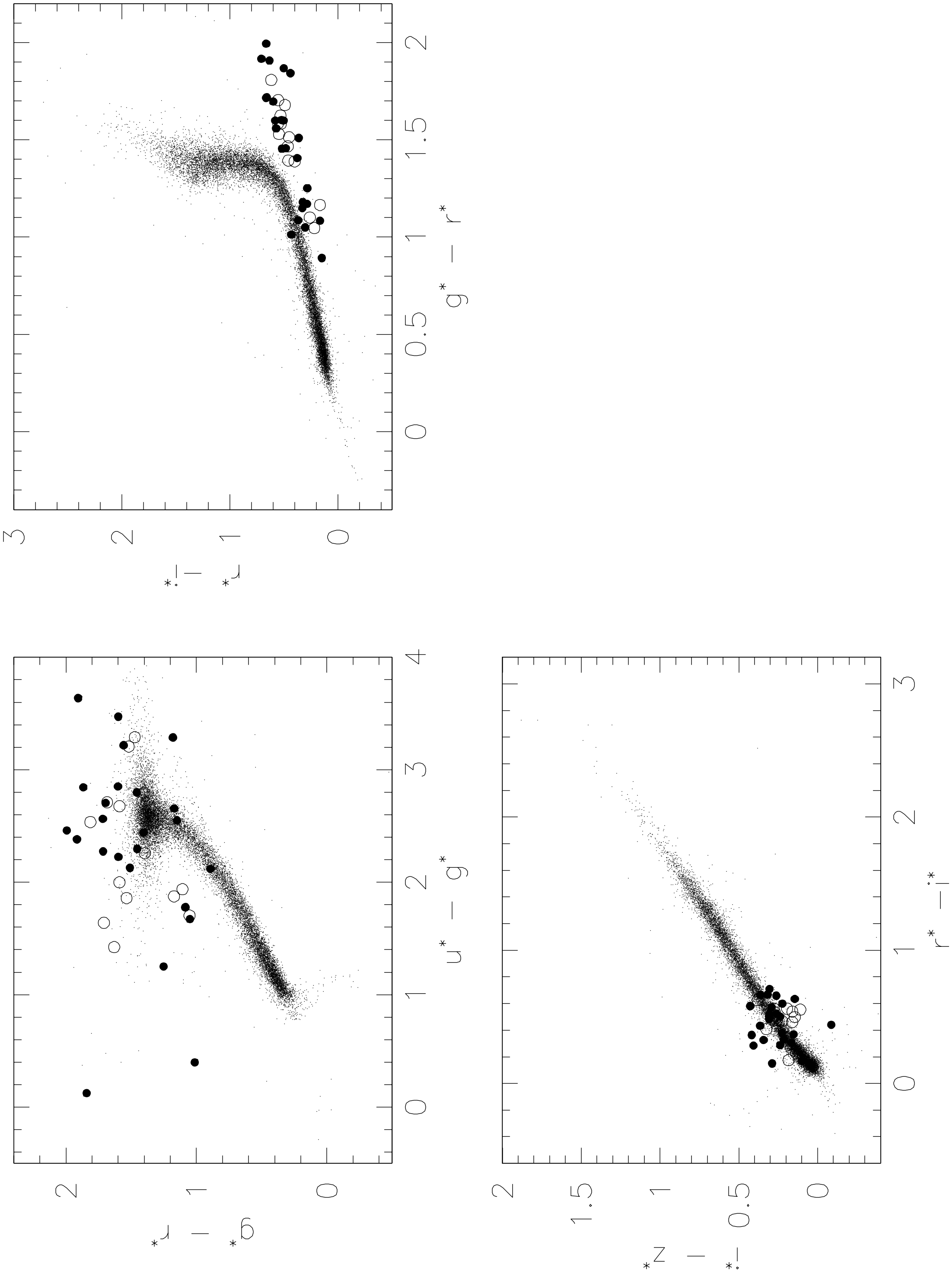
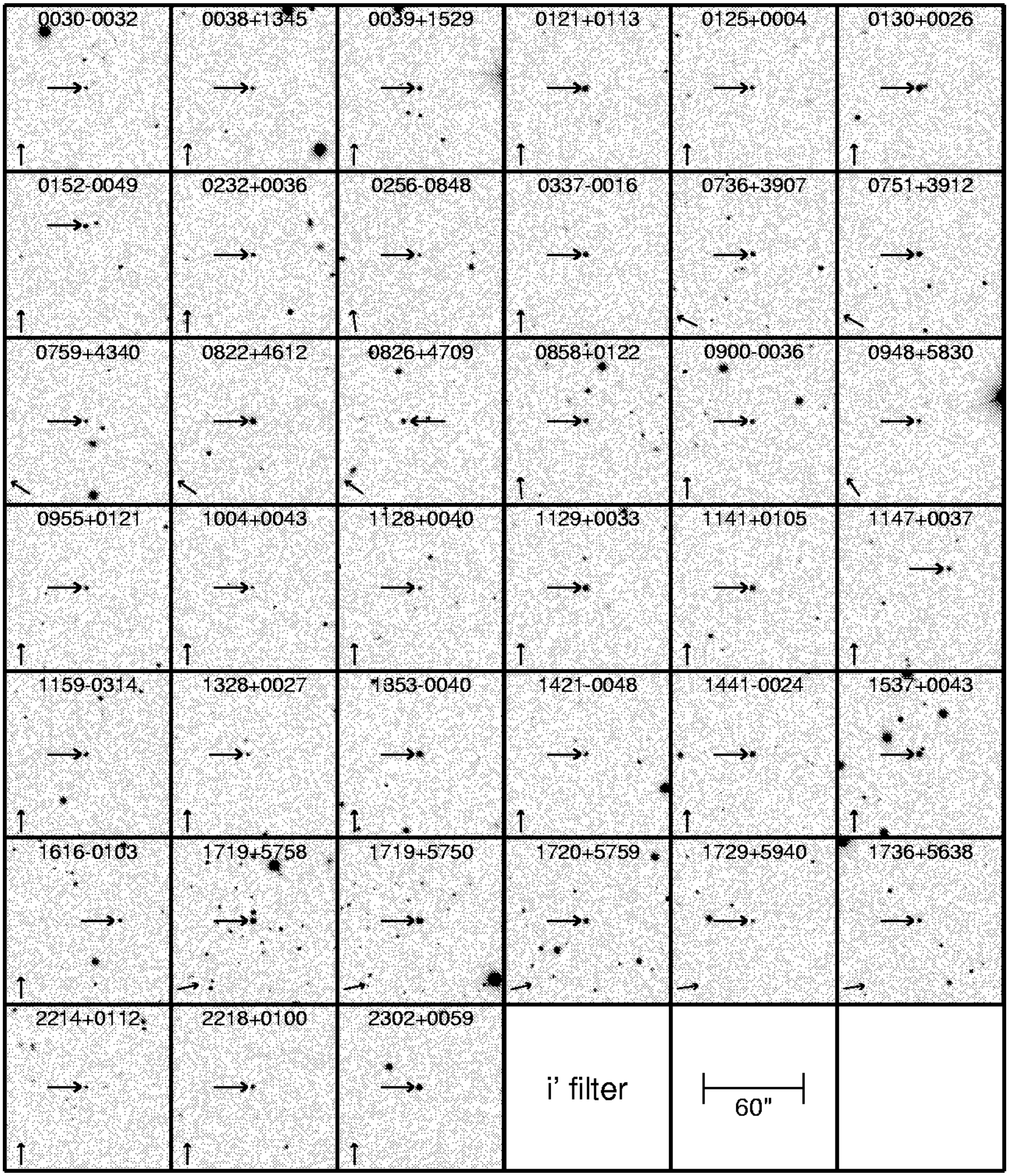
132840.7+002717
135333.0−004039
142112.4−004823
144150.9−002424
153732.2+004343
161657.6−010350
171942.4+575838
f_λ (10^{-17} erg s^{-1} cm^{-2} Å^{-1})
Wavelength (Å)
4000
6000
8000
0
2
4
6
8
10
12
20
30
40
60
80
100


171957.7+575005
172038.8+575934
172909.1+594035
173650.5+563801
221450.9+011250
221854.3+010026
230255.0+005904
f_λ (10^{-17} erg s^{-1} cm^{-2} Å^{-1})
Wavelength (Å)
4000
6000
8000
0
200
400
600
800
10
20
30
1
2
3
4
5
6
8
15
25


g* − r*
r* − i*
0
0.5
1
1.5
2
3
u* − g*
g* − r*
0
1
2
3
4
r* − i*
i* − z*
0
0.5
1
1.5
2
3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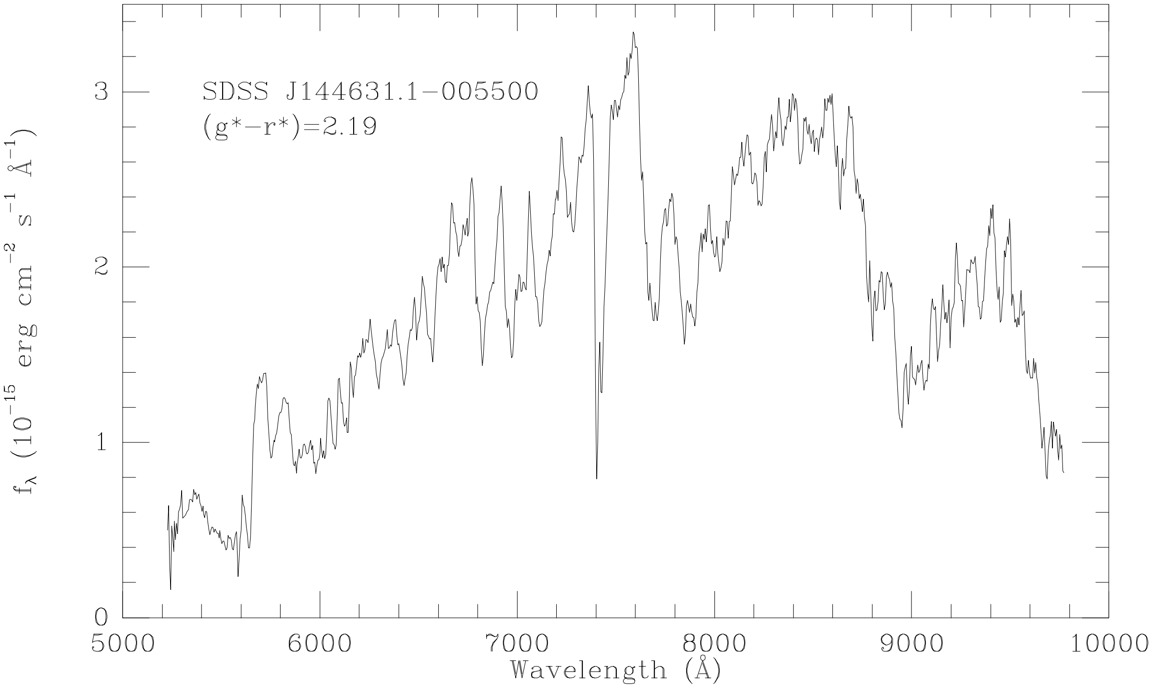
0038+1345
0039+1529
0121+0113
0125+0004
0130+0026
0152-0049
0232+0036
0256-0848
0337-0016
0736+3907
0751+3912
0759+4340
0822+4612
0826+4709
0858+0122
0900-0036
0948+5830
0955+0121
1004+0043
1128+0040
1129+0033
1141+0105
1147+0037
1159-0314
1328+0027
1353-0040
1421-0048
1441-0024
1537+0043
1616-0103
1719+5758
1719+5750
1720+5759
1729+5940
1736+5638
2214+0112
2218+0100
2302+0059
i' filter
60"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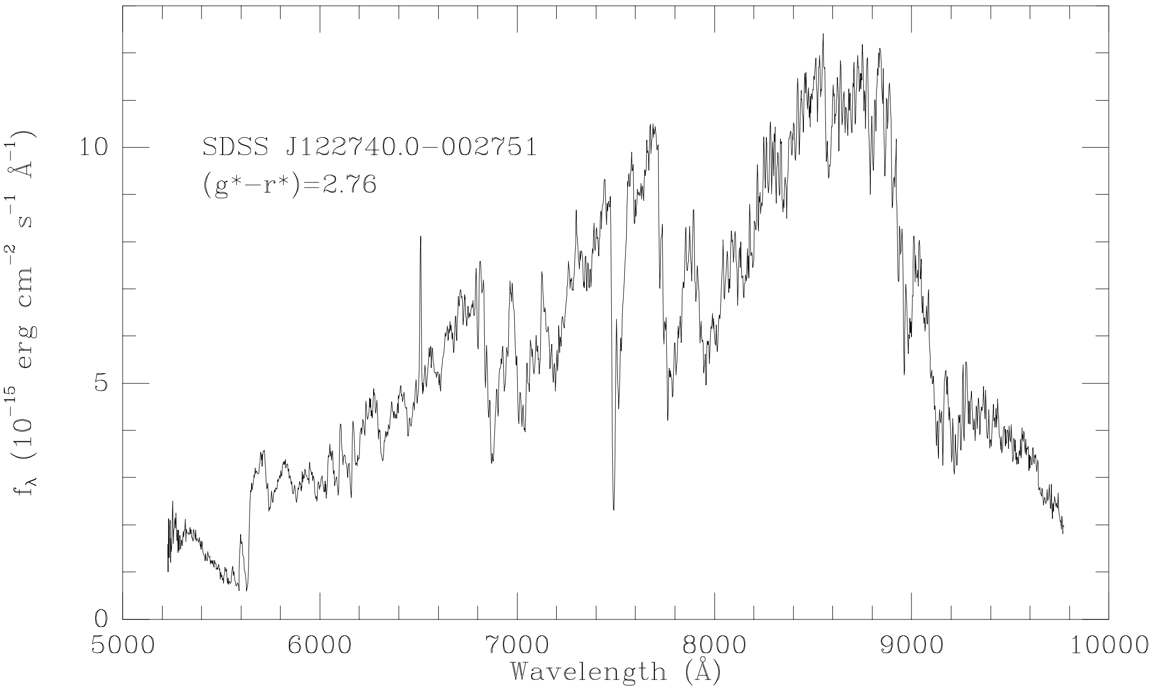
1
2
3
5000
6000
7000
8000
9000
10000
Wavelength (Å)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(g*-r*)=2.76
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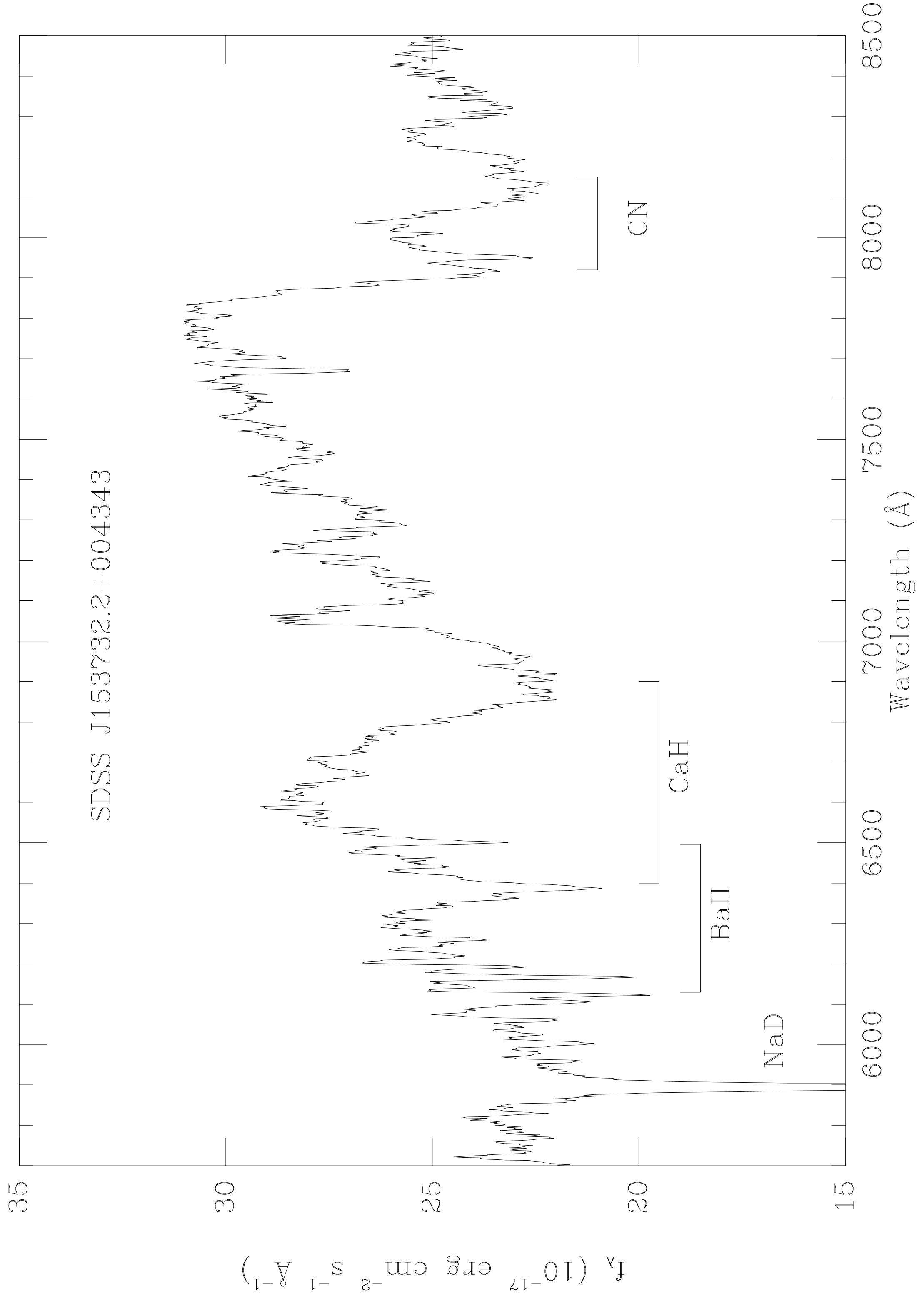
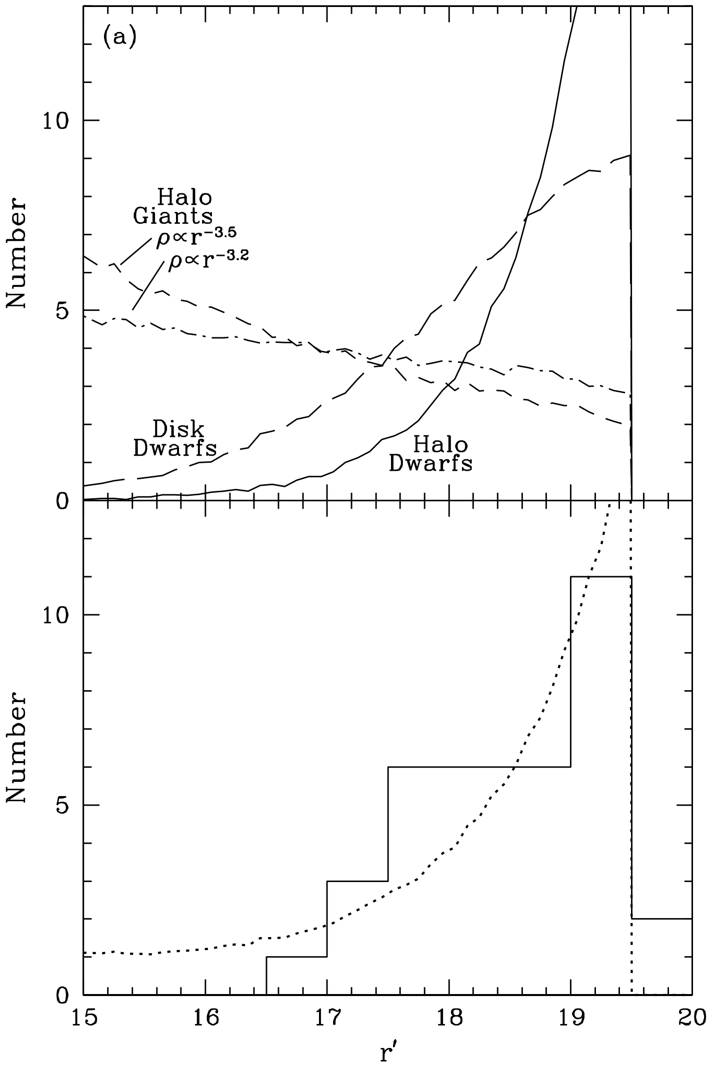
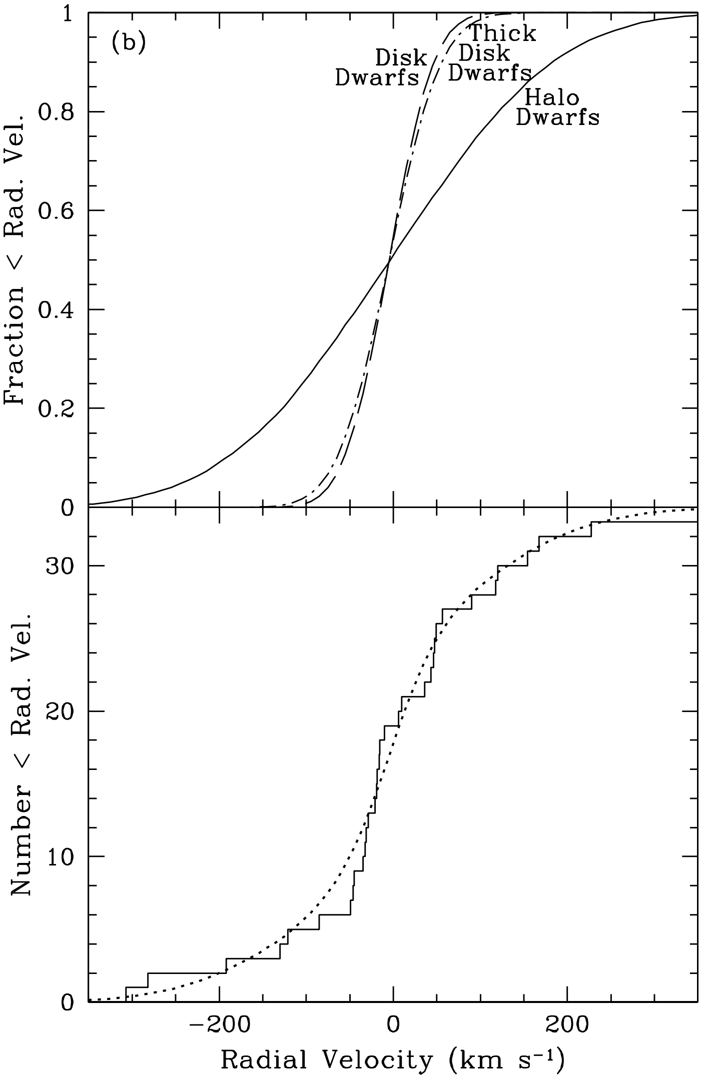
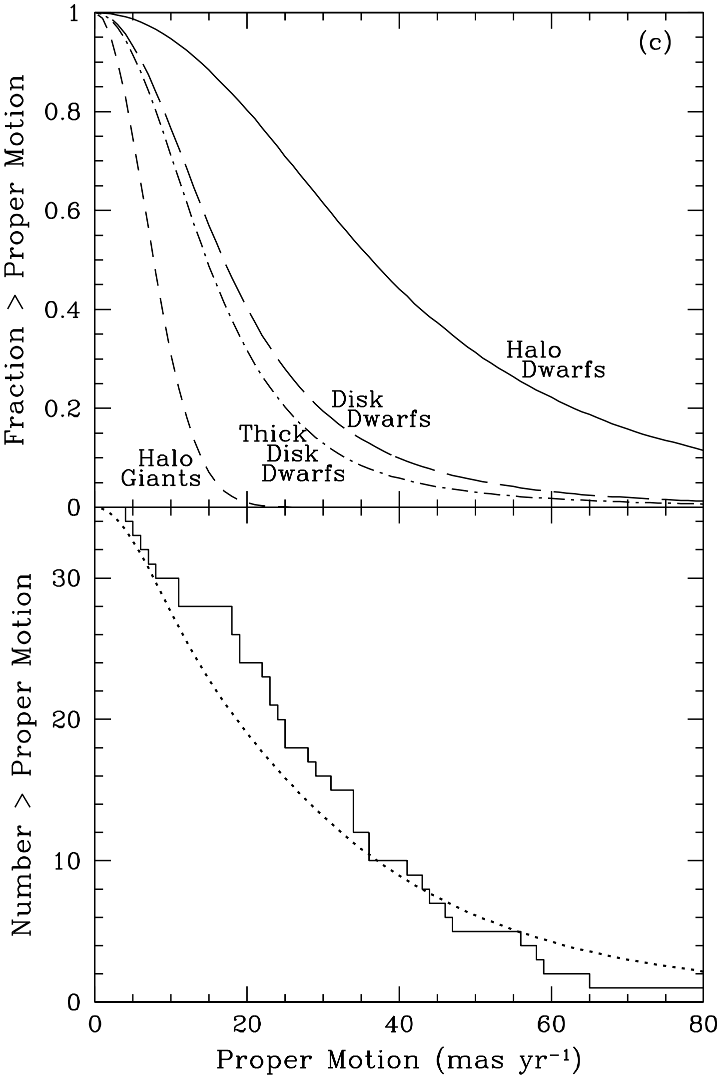
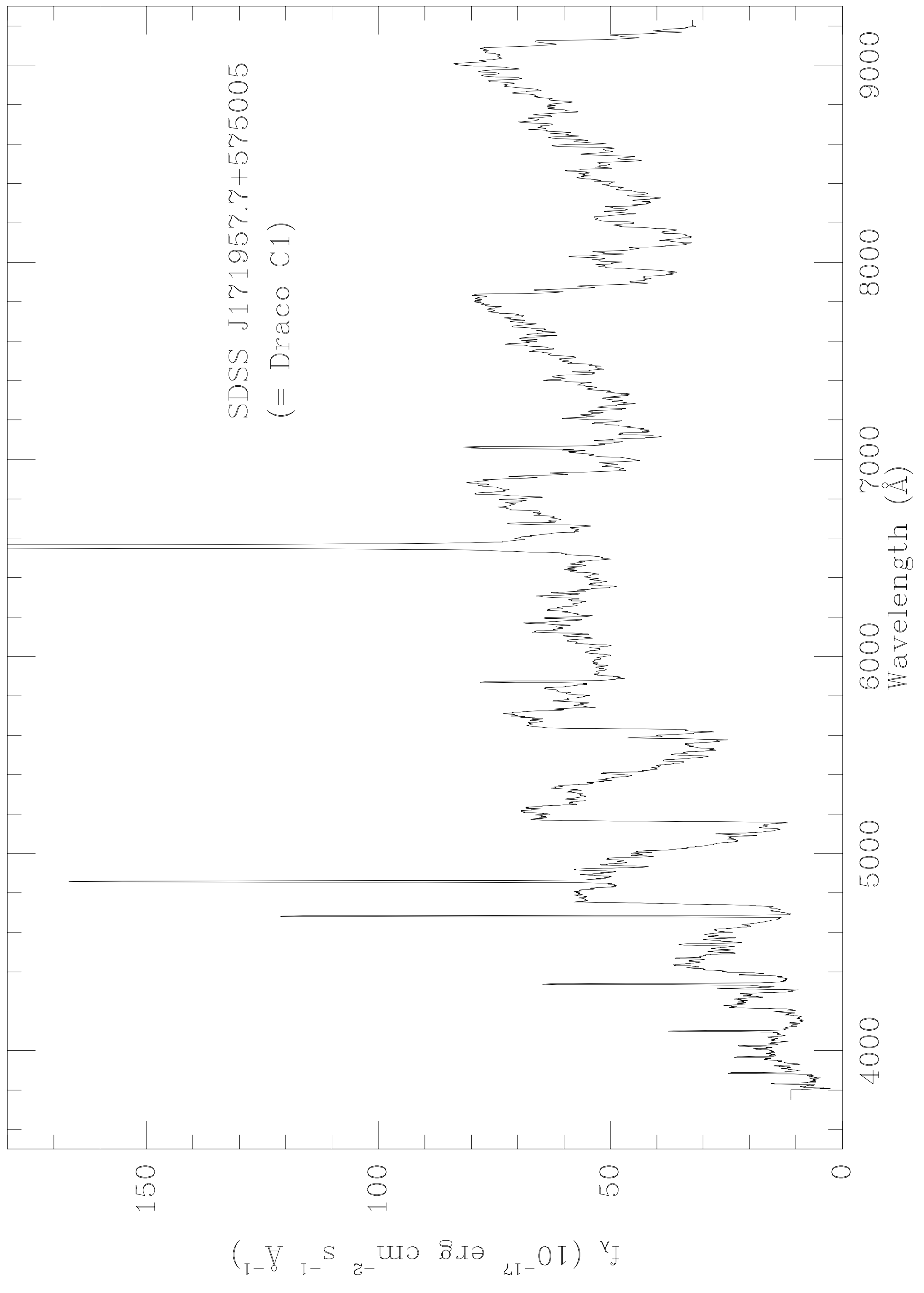
0
5
10
5000
6000
7000
8000
9000
10000
Wavelength (Å)


SDSS J153732.2+004343
NaD
BaII
CaH
CN
Wavelength (Å)
6000
6500
7000
7500
8000
8500
f_λ (10^{-17} erg cm^{-2} s^{-1} Å^{-1})
15
20
25
30
35


(a)
Number
Halo
Giants
$\rho \propto r^{-3.5}$
$\rho \propto r^{-3.2}$
Disk
Dwarfs
Halo
Dwarfs
0
5
10
Number
0
5
10
15
16
17
18
19
20
r′


(b)
Disk
Dwarfs
Thick
Disk
Dwarfs
Halo
Dwarfs
Fraction < Rad. Vel.
0
0.2
0.4
0.6
0.8
1
Number < Rad. Vel.
0
10
20
30
−200
0
200
Radial Velocity (km s^{-1})


(c)
Fraction > Proper Motion
1
0.8
0.6
0.4
0.2
0
Halo Dwarfs
Disk Dwarfs
Thick Disk Dwarfs
Halo Giants
Number > Proper Motion
30
20
10
0
0
20
40
60
80
Proper Motion (mas yr^{-1})


SDSS J171957.7+575005
(= Draco C1)
4000
5000
6000
7000
8000
9000
Wavelength (Å)
0
50
100
150
f_λ (10^{-17} erg cm^{-2} s^{-1} Å^{-1})