CANDIDATE ISOLATED NEUTRON STARS AND OTHER OPTICALLY BLANK X-RAY FIELDS IDENTIFIED FROM THE *ROSAT* ALL-SKY AND SLOAN DIGITAL SKY SURVEYS[1]

Marcel A. Agüeros,[2,3] Scott F. Anderson,[2] Bruce Margon,[4] Bettina Posselt,[5] Frank Haberl,[5] Wolfgang Voges,[5] James Annis,[6] Donald P. Schneider,[7] and Jonathan Brinkmann[8]

ABSTRACT

Only seven radio-quiet isolated neutron stars (INSs) emitting thermal X-rays are known, a sample that has yet to definitively address such fundamental issues as the equation of state of degenerate neutron matter. We describe a selection algorithm based on a cross-correlation of the *ROSAT* All-Sky Survey (RASS) and the Sloan Digital Sky Survey (SDSS) that identifies X-ray error circles devoid of plausible optical counterparts to the SDSS $g \sim 22$ mag limit. We quantitatively characterize these error circles as optically blank; they may host INSs or other similarly exotic X-ray sources such as radio-quiet BL Lac objects and obscured active galactic nuclei. Our search is an order of magnitude more selective than previous searches for optically blank RASS error circles and excludes the 99.9% of error circles that contain more common X-ray-emitting subclasses. We find 11 candidates, 9 of which are new. While our search is designed to find the best INS candidates and not to produce a complete list of INSs in the RASS, it is reassuring that our number of candidates is consistent with predictions from INS population models. Further X-ray observations will obtain pinpoint positions and determine whether these sources are entirely optically blank at $g \sim 22$, supporting the presence of likely INSs and perhaps enabling detailed follow-up studies of neutron star physics.

Key word: stars: neutron

1. INTRODUCTION

Neutron stars (NSs) were empirically confirmed first as radio pulsars (Hewish et al. 1968), and these objects continue to dominate NS statistics. Currently there are over 1500 pulsars cataloged, and the number grows steadily.[9] If one includes the number of observed X-ray binary systems (e.g., Liu et al. 2000, 2001), most of which are thought to contain a NS, $\lesssim 2000$ NSs are known. Yet a NS is born in the Milky Way every 30–100 yr, suggesting that the total population is 10^8–10^9 objects (or roughly 1% of the stars) depending on the Galaxy's star formation history (Neuhäuser & Trümper 1999). Of these NSs, only the youngest will be detected as radio pulsars, provided they are aligned favorably; after a few million years, the pulsar will have radiated away its rotational and internal energy, and the pulses will cease (Treves et al. 2000). As a result, the total number of pulsars in the Milky Way is only a few times 10^5; for every active pulsar there are ~ 1000 radio-quiet NSs (Kulkarni & van Kerkwijk 1998).

Ostriker et al. (1970) proposed that some of these defunct pulsars could reheat by accreting matter from the surrounding interstellar medium (ISM) through Bondi-Hoyle accretion. The ISM would need to be relatively dense, the NS velocity relatively low, and the NS magnetic field somewhat decayed to allow accreting matter to reach the star's surface (see also Treves &

Colpi 1991). If these conditions are met, the NS might emit approximately as a blackbody with a peak in the extreme ultraviolet/soft X-ray energy band (Treves et al. 2000). For nearby NSs this thermal emission is observable, and it was thought that *ROSAT* would detect 10^2–10^3 reheated isolated NSs (INSs), thereby potentially providing strong constraints on the NS equation of state (EOS) (see, e.g., Treves & Colpi 1991; Blaes & Madau 1993).

Yet today the list of *ROSAT*-detected radio-quiet INSs contains just seven entries (for a recent review of the so-called Magnificent Seven, see Haberl 2004). Recent work has suggested at least one plausible explanation for this discrepancy between the predicted and observed numbers of INSs: Bondi-Hoyle accretion may not be an adequate mechanism for reheating large numbers of INSs, in part because the conditions described above are unrealistic (particularly if one considers the observed pulsar velocity distribution; e.g., Perna et al. 2003). Indeed, Popov et al. (2000) have suggested instead that at the bright end of the X-ray log N- log S distribution, where most INS searches have taken place, the current number of known INSs is compatible with population models for young, cooling NSs. This is consistent with observations of the Magnificent Seven, suggesting they may have magnetic fields and velocities too large for Bondi-Hoyle accretion.

While the X-ray characteristics of the Magnificent Seven are broadly consistent with thermal emission, the current sample has managed to be both too small and too diverse in detail to definitively address the NS EOS. For example, while at least five of the Magnificent Seven are X-ray pulsars (Zane et al. 2005), the upper limit for the amplitude of X-ray pulsations in RX J1856.5−3754, the brightest known INS, is $\leq 1.3\%$ (Burwitz et al. 2003). In addition, rather than bland blackbody spectra, X-ray spectroscopy of four of the Magnificent Seven has revealed unexpected broad absorption features (Trümper 2005). The nature and significance of each of these differences are also topics of current debate (e.g., Burwitz et al. 2003; Trümper 2005; Zane et al. 2005), although some have argued that all the observational

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[2] Department of Astronomy, University of Washington, Box 351580, Seattle, WA 98195; agueros@astro.washington.edu.
[3] NASA Harriett G. Jenkins Fellow.
[4] Space Telescope Science Institute, 3700 San Martin Drive, Baltimore, MD 21218.
[5] Max-Planck-Institut für extraterrestrische Physik, Geissenbachstrasse 1, D-85741 Garching, Germany.
[6] Fermi National Accelerator Laboratory, P.O. Box 500, Batavia, IL 60510.
[7] Department of Astronomy and Astrophysics, Pennsylvania State University, 525 Davey Laboratory, University Park, PA 16802.
[8] Apache Point Observatory, P.O. Box 59, Sunspot, NM 88349.
[9] For an up-to-date catalog of known pulsars, see the Australia Telescope National Facility's database at http://www.atnf.csiro.au/research/pulsar/psrcat.

evidence is consistent with blackbody emission altered by the presence of a hydrogen atmosphere and magnetic fields of differing intensities (van Kerkwijk et al. 2004). Clearly, if we are to find unifying patterns by which to disentangle the various possible roles of magnetic fields, geometry, and atmospheres, obtaining a larger sample of INSs is required, especially to make eventual progress toward understanding the fundamental questions of the NS EOS.

In the past, a major obstacle to finding INSs was the absence of a large-area optical survey of equivalent sensitivity with which to identify the >124,000 X-ray sources cataloged in the *ROSAT* All-Sky Survey (RASS; Voges et al. 1999). The availability of a suitable companion optical survey would allow the removal of "contaminants" to INS searches (i.e., the bulk of more common X-ray-emitting subclasses: quasars, bright stars, clusters of galaxies, etc.), thereby narrowing the list of RASS error circles in which to search for new INSs. Rutledge et al. (2003) attempted to identify candidate INSs from among the 19,000 RASS sources in the Bright Source Catalog (BSC; Voges et al. 1999) by eliminating matches to the United States Naval Observatory (USNO) A2.0 optical catalog, but in the interim the Sloan Digital Sky Survey (SDSS; York et al. 2000) has emerged as a more powerful companion optical survey to RASS, especially for extending the search for new INSs to the RASS Faint Source Catalog (FSC).[10]

Here we describe a program to identify the best candidate INSs from correlations of the RASS BSC and FSC and an early version of the SDSS Data Release 4 (DR4; Adelman-McCarthy et al. 2005). In § 2 we outline the properties of the two surveys. Section 3 describes the method used to select our candidate fields, and in § 4 we describe the properties of the individual candidate fields identified by this program. Section 5 is a discussion of our results and includes a comparison of our method with that of Rutledge et al. (2003), an earlier search for INSs that also used the RASS.[11] We conclude in § 6.

2. RASS AND SDSS: A MATCH MADE IN THE HEAVENS

The RASS was the first survey of its kind in soft X-rays ($\sim$0.1–2.4 keV). Using the Position Sensitive Proportional Counter, *ROSAT* imaged the sky with exposures of lengths ranging from $\sim$400 to $\sim$40,000 s at the ecliptic equator and poles, respectively, with 99.7% of the sky observed in exposures at least 50 s long (Voges et al. 1999). The typical limiting sensitivity of the resulting RASS catalog is a few times 10^{-13} ergs cm^{-2} s^{-1}, and more than 124,000 sources are included when one merges the RASS BSC (Voges et al. 1999) and FSC.[12]

The SDSS provides a uniform optical photometric and spectroscopic data set with which to correlate the RASS catalog. SDSS is currently mapping the sky at optical wavelengths using a dedicated 2.5 m telescope at the Apache Point Observatory (APO), New Mexico, and producing homogeneous five-color *u, g, r, i, z* CCD images to a depth of $r \sim 22.5$ (Fukugita et al. 1996; Gunn et al. 1998, 2006; Hogg et al. 2001; Smith et al. 2002), with associated photometry accurate to 0.02 mag (Ivezić et al. 2004). Astrometric accuracy is better than 0″.1 per coordinate (rms) for sources with $r < 20.5$ (Pier et al. 2003); morphological information drawn from SDSS images allows for reliable star-

galaxy separation to $r \sim 21.5$ (Lupton et al. 2002). The survey's coverage of $\sim$10^4 deg^2 around the north Galactic cap and $\sim$200 deg^2 in the southern Galactic hemisphere will result in photometric measurements for over 10^8 stars and a similar number of galaxies. SDSS will also obtain spectra for 10^6 galaxies and 10^5 quasars. DR4 includes photometric data for 6670 deg^2 of sky and catalogs 1.8×10^8 objects (Adelman-McCarthy et al. 2005).

Largely by coincidence, the RASS and SDSS are extremely well matched, making SDSS an ideal tool for identifying large numbers of *ROSAT* sources (e.g., Anderson et al. 2003). In particular, if one considers the known range of f_X/f_{opt} for common X-ray emitters, even the faintest optical counterparts to typical RASS sources are bright enough to be detected in the SDSS photometric survey and targeted for SDSS spectroscopy. For the typical classes of X-ray emitters, including normal stars, normal galaxies, quasars, and BL Lac objects, the highest X-ray-to-optical flux ratios have $\log(f_X/f_{opt})$ values of about -1, 0, $+1$, and $+1.5$, respectively (e.g., Stocke et al. 1991; Zickgraf et al. 2003). Given the RASS flux limit quoted above, this implies that a faint optical counterpart in each of these categories of typical X-ray counterparts will have $m \lesssim 15,\ 17,\ 20,$ and 21, respectively, and therefore that SDSS will obtain accurate photometry for the vast majority of RASS counterparts within its footprint. [We use the Maccacaro et al. (1988) formula for calculations of $\log(f_X/f_{opt})$ and substitute *g*-magnitudes for m_V.][13] Furthermore, at these magnitudes the SDSS spectroscopic survey will frequently obtain spectra with good signal-to-noise ratios for targeted suspected counterparts, allowing for confident identifications.

3. USING SDSS TO IDENTIFY OPTICALLY BLANK RASS FIELDS

INSs, however, are not among the typical classes of X-ray emitters and have anomalously large $\log(f_X/f_{opt})$ values compared to other X-ray sources due to their optical faintness. Of the Magnificent Seven, four have suggested optical counterparts with m_V between 25.8 and 28.7 and associated $\log(f_X/f_V)$ values between 4.4 and 5.0 (Kaplan et al. 2003). Clearly, an optical counterpart to an INS is unlikely to be found using SDSS. Rather, we use SDSS to search for RASS fields devoid of plausible optical counterparts to the SDSS $m \sim 22$ limit. Such error circles host X-ray sources with such extreme f_X/f_{opt} ratios that an INS becomes a plausible identification.

We select the RASS BSC and FSC objects within the SDSS DR4 footprint by querying the DR4 database for a complete list of SDSS field positions. SDSS fields are 2048×1489 pixels and consist of the frames in the five SDSS filters for the same part of the sky. An SDSS field is in some sense the survey's smallest imaging unit in that all elements of a given field are processed by the photometric pipeline at one time. Matching the RASS positions with those of the $\sim$250,000 DR4 fields obtained, we find that $\sim$22,700 RASS sources are within the area defined by the DR4 fields, which covers 6670 deg^2. Since there are roughly three RASS sources per square degree, this number of X-ray sources in the DR4 footprint is consistent with the number of RASS sources expected from a simple surface density argument. Unlike other INS candidate searches (e.g., Rutledge et al. 2003), we do not apply a cut based on the measured X-ray hardness ratios (HR1 and HR2; see Voges et al. 1999). The Magnificent Seven have HR1 ratios that range from -1 to 0, not

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[10] Vizier Online Data Catalog, 9029 (W. Voges et al. 2000).
[11] Chieregato et al. (2005) have recently published four *ROSAT*-detected X-ray sources without optical counterparts to the Guide Star Catalog faint limit of 19–23 mag (depending on the optical band and the source position on the sky). These are High Resolution Imager observations, and the area of sky covered and the X-ray error circles are both much smaller than for the RASS.
[12] Vizier Online Data Catalog, 9029 (W. Voges et al. 2000).

[13] While *g* and m_V are not equal, the color-dependent difference between the two is relatively small [$g = m_V + 0.05$ for a typical low-redshift quasar with $(B - V) = 0.3$; Fukugita et al. 1996].

a strong constraint when the possible range is -1 to 1. While the HR2 ratio may provide a better tool with which to identify soft X-ray emitters, the uncertainties associated with the count rates for RASS faint X-ray sources make this ratio practically undetermined for many of the sources we consider here.

To find the best INS candidate fields, we search the 22,700 RASS sources for those with small X-ray positional uncertainties and select the $\sim$9500 with quoted positional errors (1 σ) smaller than $15''$ (the median RASS positional error for this sample is $13''$). In identifying counterparts to these sources in SDSS and other catalogs (and thereby eliminating them), we generally restrict our search to objects within a disk centered on the RASS position and having a radius of either $1'$ or 4 times the quoted X-ray positional error. Voges et al. (1999) provide one empirical distribution of the positional offsets of optical counterparts relative to the quoted BSC positional errors (see their Fig. 8, compiled from correlations with the Tycho catalog; Hog et al. 1998). An examination of their most reliable matches indicates that this distribution is not adequately described overall by a two-dimensional Gaussian and that a one-dimensional Gaussian may be a better fit at larger multiples of the quoted positional error. We therefore estimate that among the 9500 sources we consider further, fewer than 1 are expected to have a counterpart with a positional offset larger than 4 times the *ROSAT* X-ray positional error. For simplicity, we describe this search radius in the rest of the text as equal to 4p.e. (for positional error) and the associated error circle as the 4p.e. error circle.

Previous work suggests that roughly one-third of the $\sim$9500 sources with small positional errors are quasars and that another third are bright stars (e.g., Zickgraf et al. 2003). We therefore match the 9500 sources with small positional errors to the most recent SDSS catalog of >4000 spectroscopically identified RASS quasars (e.g., Anderson et al. 2003). We take $1'$ as our matching radius, meaning that any X-ray source with a spectroscopically confirmed quasar within an error circle of radius $\geq$4p.e. is eliminated from further consideration. Similarly, we use the SDSS DR4 photometric catalog to eliminate RASS fields with a $g < 15$ mag object[14] within $1'$. When querying the DR4 database we request "primary" photometry, which requires that objects have a single entry in the database, that they not be deblended, and that they fall within the survey boundaries (for details, see Stoughton et al. 2002). The median count rate for our sample of RASS sources with small positional errors is 0.034 counts s^{-1}, so that $g < 15$ objects have $\log(f_X/f_g) \lesssim -1.1$ and are most probably the X-ray source counterparts (see Table 1 in Stocke et al. 1991). Both of these cuts are extremely conservative, as they are applied without specific f_X/f_{opt} restrictions and extend to a large positional offset for each source. Still, a confirmed quasar, or a bright star or galaxy, even with an atypical f_X/f_{opt} and at a large positional offset, might be a more plausible identification than an INS. Roughly half of the 9500 originally selected sources with small positional errors remain at the end of this stage of our algorithm.

To reduce the number further, we use the DR4 database to eliminate X-ray error circles with any UV-excess objects. These are objects satisfying $u - g < 0.6$ and $u \leq 22.0$, the SDSS 95% completeness limit (Stoughton et al. 2002); for the most part, these are candidate (photometric) quasars (e.g., Richards et al. 2002), but this cut also identifies and removes white dwarfs and cataclysmic variables (CVs)/X-ray binaries. Here we calculate the separation between each such object and the RASS source and eliminate those fields in which a UV-excess object falls within the 4p.e. error circle of the associated X-ray source. Finally, because the occasional pathologically bland quasar (a few percent of all cases; Vanden Berk et al. 2001) or a quasar in a selected redshift range can have colors consistent with those of normal stars and cannot easily be identified using SDSS-color cuts, we remove fields with objects that have quasar-like X-ray-to-optical flux ratios [defined as $\log(f_X/f_g) \leq 1.2$, the typical upper limit for active galactic nuclei (AGNs) given by Stocke et al. (1991)] *regardless of their optical colors*. We eliminate all fields in which such an object with $g \leq 22.2$ (the 95% completeness limit in that band) is cataloged within 4p.e. of the X-ray position. This removes about four-fifths of the remaining sources, leaving us with 410 X-ray sources, about 4% of our initial sample of RASS sources with small positional errors.[15]

We then require, when matching these sources to the SDSS catalog, that SDSS primary photometry within the 4p.e. error circle be available, thereby eliminating false-positive fields that would otherwise be defined as optically blank at this stage of the algorithm only because there is no reliable SDSS photometry for them. Over 80% of the 410 fields lack SDSS photometry; this is frequently because of the presence of a saturating star or because the RASS source falls on the edge of the DR4 footprint. The remaining 74 RASS sources are then fed to SIMBAD and the NASA/IPAC Extragalactic Database (NED), with which we eliminate 19. Roughly half of these sources are cataloged clusters within $1'$, while the rest include known BL Lac objects or bright Two Micron All Sky Survey galaxies within the 4p.e. error circle. We also eliminate the 22 X-ray error circles with a cataloged NRAO VLA Sky Survey (NVSS; Condon et al. 1998) or VLA Faint Images of the Radio Sky at Twenty cm (FIRST; Becker et al. 1995) source within 4p.e. of the associated X-ray position; this is intended especially to eliminate uncataloged BL Lac candidates. These steps reduce the list of candidates to 33 RASS X-ray error circles.

Visual inspection of the SDSS images of these remaining 33 fields finds three cases with an obvious candidate optical counterpart to the X-ray source that has somehow evaded our algorithm. In two cases the most likely explanation is the absence of primary SDSS photometry for a bright star present in the center of one field and for a galaxy in the center of the other. In the third case, SDSS spectroscopy of a $g = 20.44$ object reveals it to be an emission-line galaxy and therefore a conceivable (though unusual) X-ray source. We eliminate these fields and are left with a list of 30 X-ray error circles that are optically blank (devoid of plausible optical counterparts) at the SDSS catalog level as defined by our algorithm.

Visual inspection of the *ROSAT* hard- and soft-band images of these 30 fields allows us to eliminate nine RASS sources from further consideration. These eliminated sources include possible artifacts and extended or very uncertain X-ray detections. Among the RASS sources eliminated at this stage is 1RXS J115309.7+545636, one of the sources observed with the *Chandra X-Ray Observatory* as a candidate INS by Rutledge et al. (2003). Their observations confirmed that 1RXS J115309.7+545636 is in fact not an INS (see § 5.1).

Three additional RASS sources were set aside at this stage. Their quoted positional error of $6''$ appears to be an underestimate

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[14] In querying the database for photometry, we request both PSF and model magnitudes and make our cuts based on both. Typically, PSF fitting provides better estimates of isolated star magnitudes, while model fitting is best for galaxies. See Stoughton et al. (2002).

[15] This cut is sufficiently stringent that it may render some of the previous steps unnecessary. However, it would not alone eliminate spectroscopically confirmed SDSS BL Lac objects, for example, a significant fraction of which do have $\log(f_X/f_g) > 1.2$ (Anderson et al. 2003).

TABLE 1
X-Ray and Optical Data for the 11 Candidate Isolated Neutron Star Fields

Source Name: 1RXS J	ROSAT				SDSS	
	1σ (arcsec)	Count Rate $(10^{-2}$ counts s$^{-1})$	Detection Likelihood	Exposure Time (s)	g-magnitude	Minimum $\log(f_X/f_g)$
003413.7−010134[a]	14	1.3 ± 0.6	10	630	23.22	1.8
013630.4+004226[a]	13	2.5 ± 1.0	16	283	21.82	1.5
092310.1+275448	14	2.5 ± 1.0	14	407	21.74	1.5
103415.1+435402	14	1.7 ± 0.8	9	502	21.66	1.3
110219.6+022836	15	1.8 ± 0.8	11	423	21.80	1.3
122344.6+373015	15	2.8 ± 1.1	11	490	21.97	1.6
130547.2+641252[b]	9	16.7 ± 2.1	122	544	22.05	2.4
131400.1+072312	15	1.8 ± 1.0	8	333	21.69	1.3
141428.5+601707	14	1.4 ± 0.7	9	630	21.99	1.3
151855.1+355543	9	3.3 ± 0.9	32	518	21.04	1.3
160518.8+324907[c]	7	87.5 ± 4.1	1140	566	22.80	3.4

[a] Outside of optical cluster catalog footprint.
[b] Rejected as an INS by Rutledge et al. (2003).
[c] Known INS.

if one considers the count rates and exposure lengths for these sources (see the Appendices for further discussion).

Some fraction of the remaining X-ray sources are likely to be associated with optically faint clusters of galaxies. We therefore correlate our remaining X-ray positions with a catalog of optically selected SDSS clusters (J. Annis 2005, private communication). Two of our X-ray sources fall outside of the cluster catalog's footprint and were therefore not subject to this cluster analysis; see Table 1. The optical clusters are described in part by their n_{gal} value, the number of red-sequence galaxies brighter than $0.5L_*$ within a 1 Mpc radius volume, with SDSS colors providing a photometric estimate of the redshifts. If there is a candidate cluster with $n_{gal} \geq 3$ with an offset $\leq 1'$ from the X-ray position, we eliminate the X-ray source as a candidate INS. This removes two RASS sources from consideration and is consistent with our elimination, earlier in our algorithm, of cases with a cataloged NED/SIMBAD cluster within $1'$.

In identifying clusters at larger angular separations as likely RASS X-ray sources, we take $5'$ as our maximum separation for considering matches. There is a drop-off in the surface density of candidate SDSS optical clusters at that separation. We choose $n_{gal} \geq 6$ as our richness criterion for considering a cluster to be a likely X-ray source in these high positional offset cases and thereby eliminate another five RASS error circles as candidate clusters (see the Appendices for further discussion of these candidate clusters).

These steps winnowed the original list of 9500 RASS sources in the SDSS DR4 footprint to 11 X-ray sources that are bereft of plausible counterparts and are therefore candidate blank-field X-ray sources. It is highly reassuring that among these surviving blank field X-ray sources is the field containing RX J1605.3+3249, the only previously known INS in the SDSS DR4 footprint. We argue in § 5.1 that our selection using SDSS is an order of magnitude more stringent than the Rutledge et al. (2003) hallmark blank-field search for INSs.

4. PROPERTIES OF THE CANDIDATE ISOLATED NEUTRON STAR FIELDS

The 11 fields discussed in this section are those that survived our winnowing algorithm and are most likely to harbor either INSs or some other rare and exotic X-ray emitter such as radio-quiet BL Lac objects, obscured AGNs, and dark clusters. They

include one previously rejected candidate INS field (Rutledge et al. 2003), as well as the field of RX J1605.3+3249, the only known INS falling within the SDSS DR4 footprint. Figure 1 is a mosaic of the SDSS composite g, r, i images of all 11 of the candidate fields with the RASS 4 p.e. error circles superposed. Table 1 includes the ROSAT parameters for all of these RASS sources (count rate, detection likelihood, and exposure time; see Voges et al. 1999), as well as the g-magnitude of the brightest SDSS object within the 4 p.e. RASS error circle and the corresponding minimum $\log(f_X/f_g)$ for the optical counterpart to the X-ray source.

Below we provide additional information about several of these X-ray sources: those that might have viable optical counterparts at unexpectedly large positional offsets and those previously identified in the literature as INS candidates.

4.1. New Candidate INS Fields with Other Possible Counterparts at Large Offsets

There are two candidate INS fields in which a known quasar or a bright star lies just outside the 4 p.e. RASS error circle. Although we expect <1 case of an optical counterpart being found at such large positional offsets from our entire starting set of 9500 RASS X-ray sources, in this section we call special cautionary attention to these cases. Good angular resolution X-ray images would quickly resolve such issues definitively. These two cases are:

1RXS J003413.7−010134: The 4 p.e. error circle just barely excludes a $g = 16.75$ star for which we obtained a spectrum with the 3.5 m telescope at APO, New Mexico. This spectrum is that of a G star with no emission; the star's $\log(f_X/f_g)$ of -0.8 is unlikely for G stars, whose (log) flux ratios are typically between -4.3 and -2.4 (see Table 1 of Stocke et al. 1991), suggesting that it is probably not the X-ray source.

In addition, we note the presence of a spectroscopically confirmed quasar, SDSS J003413.04−010026.8, $1\rlap{.}'13$ (4.8 times the quoted RASS positional error) from this source. This $g = 17.20$ quasar has a $\log(f_X/f_g) = -0.63$, within the range for AGNs given by Stocke et al. (1991) of -1 to 1.2.

1RXS J141428.5+601707: A spectroscopically confirmed quasar, SDSS J141431.67+601807.2, lies $1\rlap{.}'09$ (4.7 times the quoted RASS positional error) from this source. This quasar has
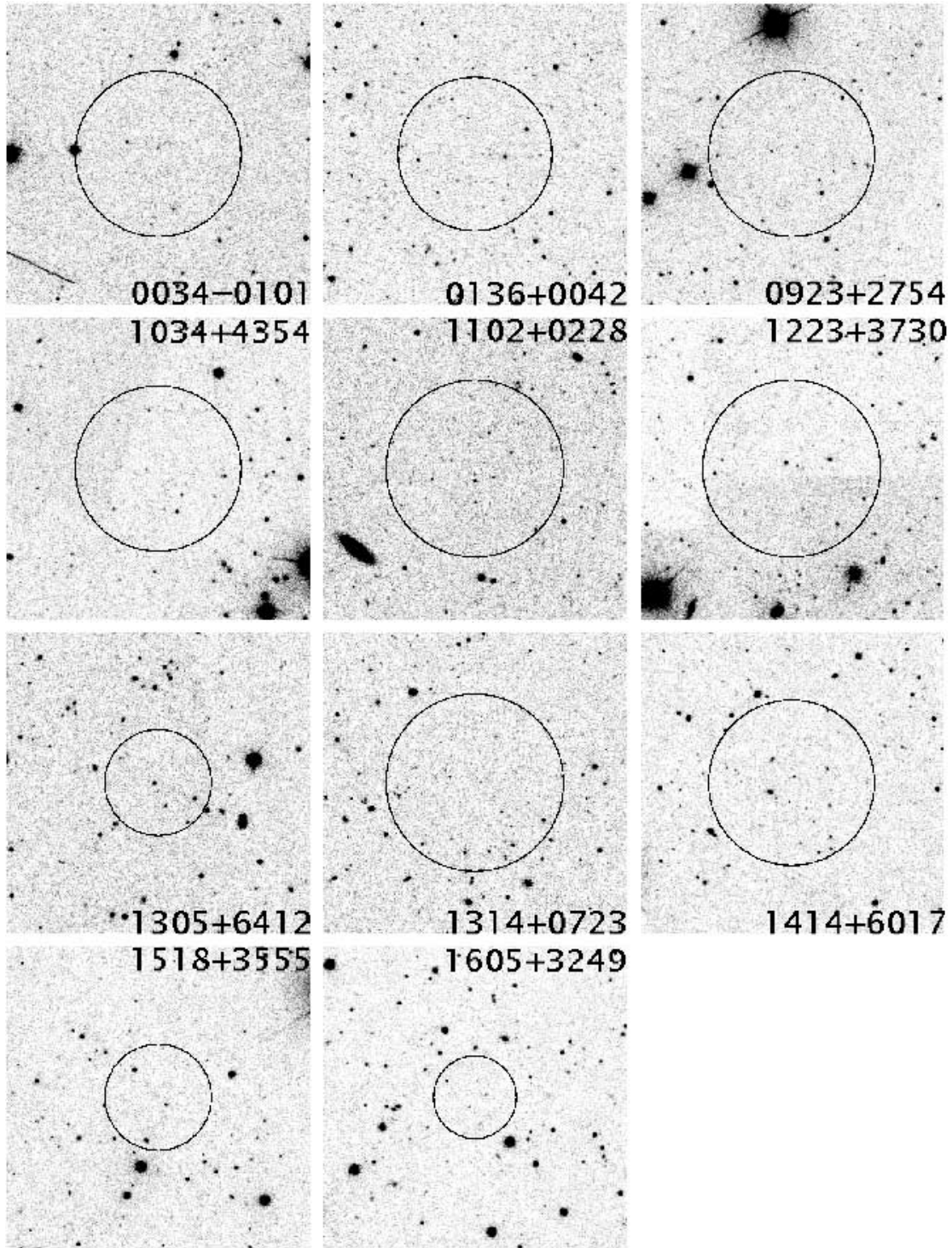
Fig. 1.—SDSS composite *g*, *r*, *i* images of our best INS candidate fields, with the stretch being the same for all. North is up and east is to the left, and the images are roughly 3′.5 on a side. The 4p.e. RASS positional error circle is shown in each image. The brightest SDSS object within any of the 4p.e. error circles is $g = 21.04$ mag. Rutledge et al. (2003) rejected IRXS J130547.2+641252 as an INS; IRXS J160518.8+324907 is a known INS.

$g = 17.82$ mag, so that its $\log (f_X/f_g) = -0.36$, within the range for AGNs given by Stocke et al. (1991).

4.2. *Previously Known Candidate INS Fields*

There are two previously suggested candidate INSs that are also included among our 11 candidates. One is a confirmed INS, while the other was later refuted as an INS:

1RXS J130547.2+641252: This source was proposed and rejected as a candidate INS by Rutledge et al. (2003) because of its X-ray variability (see § 5.1.1 for further discussion).
1RXS J160518.8+324907: This is the only previously known INS in the SDSS DR4 footprint. It is very reassuring that this confirmed case is recovered by our algorithm.

5. DISCUSSION

5.1. *Comparison with Previous Work*

An important effort involving RASS/optical selection of candidate INSs was that of Rutledge et al. (2003). Rutledge et al. (2003) identified candidate INS fields by correlating the RASS BSC with the NVSS, the *Infrared Astronomical Satellite* Point Source Catalog, and the USNO A2.0 optical catalog. They obtained a list of 32 candidate blank-field RASS sources (including two known INSs), from which they selected eight for *Chandra* observations. None of these eight sources was found to be an INS (Rutledge et al. 2003).

The current availability of both SDSS spectroscopy and much deeper SDSS photometric data—2 or 3 mag fainter than USNO A2.0—permits us to invoke a much more stringent set of selection criteria. To compare our method with that of Rutledge et al. (2003), we discuss the properties of the 11 candidate fields from their original list of 32 that fall within the SDSS DR4 footprint, as well as those of the six of their eight *Chandra* targets that do not fall within the SDSS footprint but for which Rutledge et al. (2003) provide Digitized Sky Survey (DSS) data. Finally, we speculate on how the remaining 15 Rutledge et al. blank-field candidates would fare at the hands of our algorithm *if* they were in the SDSS DR4 footprint.

5.1.1. *Rutledge et al.* (2003) *Sources within SDSS DR4*

Of the initial 32 Rutledge et al. (2003) candidate sources, 11 fall within the DR4 footprint, including the previously known INS, RX J1605.3+3249. All 11 candidates were processed by our winnowing algorithm in a double-blind, end-to-end fashion. Reassuringly, RX J1605.3+3249 survives our algorithmic selection and is among our 11 INS candidates.

Six of the remaining 10 Rutledge et al. (2003) sources, for which they identified "ordinary" optical counterparts, were eliminated early on by our algorithm. One (1RXS J091010.2+481317) disappears from our list of candidate sources when matched against spectroscopically confirmed SDSS quasars, three (1RXS J104710.3+633522, J130402.8+353316, and J130753.6+535137) are eliminated because of the presence of candidate photometric SDSS quasars,[16] and two (1RXS J123319.0+090110 and J130034.2+054111) fail our test for sources with no objects brighter than $g = 15$ within $1'$. A seventh source, 1RXS J094432.8+573544, is eliminated when our X-ray sources are matched to the radio catalogs; it also has an SDSS spectrum, which suggests that it is a BL Lac object.

Two of the three other sources survive to the last stages of our algorithm before being eliminated. Visual inspection of the

RASS images of 1RXS 115309.7+545636 reveals it to be an extended source, and it is therefore eliminated as a candidate INS by our algorithm. The object 1RXS J145234.9+323536 is identified as a candidate optical cluster and is also removed from our list of INS candidates (see the Appendices). Rutledge et al. (2003) obtained *Chandra* observations of both of these sources and did not detect an X-ray source in either case.

Only one of the remaining 10 Rutledge et al. (2003) sources, 1RXS J130547.2+641252, survives to make our list of the best candidate INSs. Rutledge et al. (2003) rejected this source as a candidate based on its X-ray variability, measured by comparing its RASS data to observations of the same source with the High Resolution Imager on *ROSAT*. We queried the *Chandra* and *XMM-Newton* lists of observed targets, as well as the various *ROSAT* catalogs, and found that none of our other INS candidates has the complementary X-ray observations required for the detection of such variable or transient sources. We therefore cannot discount the possible contamination of our candidate list by such sources.

In summary, of the 11 Rutledge et al. (2003) candidate INS fields that fall within the DR4 footprint, only two survive our winnowing process. One is a likely transient or variable source, previously discounted as an INS via *Chandra* observations by Rutledge et al. (2003). The other is a successful recovery of the one previously confirmed INS in the SDSS DR4 imaging area, RX J1605.3+3249. Our algorithm is therefore significantly more efficient at removing contaminants from our candidate list while simultaneously recovering the only previously confirmed INS in the SDSS DR4 footprint.

5.1.2. *Sources for Which Rutledge et al.* (2003) *Provide DSS Data*

Rutledge et al. (2003) also obtained *Chandra* observations for six sources that do not fall within the SDSS DR4 footprint. However, Rutledge et al. do discuss the DSS photometric properties of these six sources: for three they find fairly bright likely optical counterparts, and for three they find counterparts near the DSS faint limit, all offset from the RASS source by less than 3 times the quoted positional error. While these six sources are not in the DR4 footprint, it is almost certain that if they had been, none would have made our list of candidate INSs.

In three of the X-ray error circles (1RXS J024528.9+262039, J132833.1−365425, and J163910.7+565637), Rutledge et al. (2003) identify the likely optical counterparts as two $B \sim 15$ late-type stars and a $B = 17.8, z = 1.65$ quasar, respectively. With SDSS data, the magnitudes of the late-type stars and/or their f_X/f_{opt} ratios (approximately -0.5 and -0.9, respectively, within the range for M stars in Stocke et al. [1991]) would very likely have caused our algorithm to eliminate these error circles and perhaps even suggested the proper identifications. The low-redshift quasar's colors might have been unusual, causing our algorithm to remove it from our candidate list early on; if not, its f_X/f_{opt} ratio (~ 0.2) likely would also have caused it to be eliminated by our algorithm (an SDSS spectrum might also have been available).

In the other three cases (1RXS J020317.5−243832, J145010.6+655944, and J122940.6+181645), SDSS photometry would be available, as the SDSS faintness limit is $\sim 2-3$ mag deeper than the DSS limit, depending on the band. Rutledge et al. suggest a faint CV and two faint AGNs as the optical counterparts to these X-ray sources. The colors of the objects, again along with their f_X/f_{opt} ratios, would probably have disqualified these fields from further consideration.

Our algorithm therefore would probably have eliminated all six of these additional sources observed with *Chandra* by Rutledge et al. (2003), none of which were confirmed as an INS.

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[16] This eliminates the fields with known cataclysmic variables (1RXS J104710.3+633522 and J130753.6+535137), as these also have $u - g \leq 0.6$.

5.1.3. *Other Rutledge et al. (2003) Sources*

There remain 15 sources that Rutledge et al. (2003) initially considered as candidate INSs but ultimately rejected in post-algorithmic screening. The optical content of these RASS error circles as described by Rutledge et al., or as directly determined from DSS images by us, is such as to virtually guarantee that 14 would be rejected by our algorithm *if* they fell within the SDSS footprint. These fields include 12 with bright stars, a CV in the globular cluster M3, and a known Seyfert 1 galaxy. The 15th source is another known INS, RX J1308.6+2127.

In summary, these comparisons verify that our algorithm, relying especially on the greater optical photometric depth of SDSS, successfully recovers the only previously known INS in our survey area and also rejects an order of magnitude more contaminating RASS error circles than the Rutledge et al. (2003) search for INSs.

5.2. *Comparison with Galactic INS Population Models*

The current dearth of candidate INSs beyond the Magnificent Seven has led to several efforts to rethink the expected population of INSs within the Galaxy. In particular, Popov et al. (2000) compared the space density of accreting (i.e., reheated and old) INSs to that of cooling (i.e., young) NSs using a number of assumptions about, for example, the Galactic NS birth rate, the large-scale distribution of gas in the ISM, and the cooling time for a newborn NS.

Popov et al. (2000) find that at the bright end (*ROSAT* count rates ≥ 0.1 counts s^{-1}, $L_X \sim 10^{29}-10^{30}$ ergs s^{-1}), the predicted population of INSs is essentially just the small number of young NSs seen at an early enough evolutionary stage—the first 10^6 years of their lives—to still be quite hot. They also find that these coolers are typically 3 orders of magnitude brighter than accreting, older INSs. However, the total number of predicted accretors is about 2 orders of magnitude larger than that of coolers, so that at lower count rates/X-ray fluxes the number of accretors is comparable to that of coolers. Indeed, Popov et al. (2000) predict that at fluxes below $\sim 10^{-13}$ ergs cm^{-2} s^{-1} the number of accretors exceeds the number of coolers. The overall Popov et al. (2000) prediction for the Galactic INS population is consistent with current observations, if one assumes that the Magnificent Seven are indeed all young, bright coolers. Interestingly, it also suggests that at the fainter flux limits of the RASS FSC there are a significant number of as-yet undetected INSs.

Of the ~ 9500 RASS X-ray sources with small positional errors from which we selected our candidate INSs, 80% have count rates ≥ 0.017 counts s^{-1}, and we adopt this value as a rough lower limit to our search sensitivity. This corresponds to the peak in the cumulative distribution of count rates for our sample and is also consistent with the value of the flux for which Shen et al. (2006) quote a 50% completeness level for RASS detections in the SDSS Data Release 1 area. Popov et al. (2000) predict that the total number of INSs with count rates greater than this limit should be $3-10$ sr^{-1}, or $40-125$ over the entire sky. Based on their models, a naive prediction is that the SDSS DR4 area contains $5-20$ INSs, a range consistent with the number of new candidates we identify here. We note, however, that our list is not complete: it is very likely that good INS candidates were lost because of their chance proximity to unrelated SDSS objects, which caused our algorithm to eliminate those RASS error circles from consideration.

6. CONCLUSION

In an effort to expand the sample of known INSs, we have developed a selection algorithm based on a cross-correlation of the RASS and SDSS data to identify X-ray error circles devoid of plausible optical counterparts. We use SDSS spectroscopy and, especially, deep SDSS DR4 photometric data to quantitatively characterize the 11 RASS fields that survive our winnowing algorithm as optically blank to the SDSS $g \sim 22$ mag faint limit. Our search is an order of magnitude more selective than similar previous searches for optically blank RASS error circles; in selecting our INS candidates, we have excluded 99.9% of the RASS error circles in our initial sample.

The 11 RASS fields we identify as potentially hosting an INS include the only confirmed INS in the DR4 footprint, RX J1605.3+3249, along with 1RXS J130547.2+641252, previously considered as an INS candidate and rejected on the basis of *Chandra* observations (Rutledge et al. 2003). The remaining nine new candidates may host INSs or other similarly exotic X-ray sources, such as unusual X-ray binaries, high-redshift quasars, dark clusters of galaxies, type 2 quasars, or extreme BL Lac objects (e.g., Chieregato et al. 2005).

We note that the number of candidates we find is consistent with the predictions from recent INS population models for the number expected in the SDSS DR4 footprint. Planned *Chandra* follow-up observations of these candidate fields will help confirm whether they contain INSs or some alternate exotic X-ray emitters. At the minimum, our sample may help increase the diversity of NSs available for study.

APPENDIX A

ADDITIONAL INTERESTING FIELDS

In addition to the candidate fields listed in Table 1 and discussed in § 4, we present a number of interesting X-ray fields identified in the process of developing the algorithm described above. These fields can be divided into two groups. The first seven are candidate faint optical clusters that failed the last step in our algorithm (see Fig. 2). The other group is of six fields that barely fail the final version of the algorithm (all but one were correlated with the cluster catalog without being eliminated, however; see Fig. 3). While this is not a complete list of either potential new RASS/SDSS clusters or of interesting fields not quite good enough to make our final list, it does provide a sense of the properties of X-ray fields considered borderline optically blank by our algorithm.

Table 2 includes the main *ROSAT* parameters for these RASS sources and the g-magnitude of the *brightest* SDSS object within the 4p.e. RASS error circle and the corresponding *minimum* $\log (f_X/f_g)$ for the optical counterpart. Below we give additional information about a number of these fields.

APPENDIX A1

CANDIDATE CLUSTERS WITH OTHER POSSIBLE OPTICAL COUNTERPARTS

In this section we list candidate clusters identified by our program in which another plausible optical counterpart to the X-ray source is also present (see § 3 for a discussion of the cluster identification stage of our algorithm).

1RXS J102659.6+364039: Two potential optical counterparts to this X-ray source are cataloged by Zickgraf et al. (2003). However, both are too faint ($B > 20$) to be unambiguously identified by Zickgraf et al. as the X-ray source. To our knowledge no spectrum of either of these potential counterparts has been taken.

1RXS J130723.7+095801: Three optical objects within $1'$ of this X-ray source are cataloged by Zickgraf et al. (2003). Again, however, these are too faint ($B > 19$) to be unambiguously identified by Zickgraf et al. as the X-ray source; no spectra of these potential counterparts exist to our knowledge.

1RXS J155705.0+383509: This is a source with a bright ($g = 15.10$) star near the edge of its 4p.e. error circle. We obtained
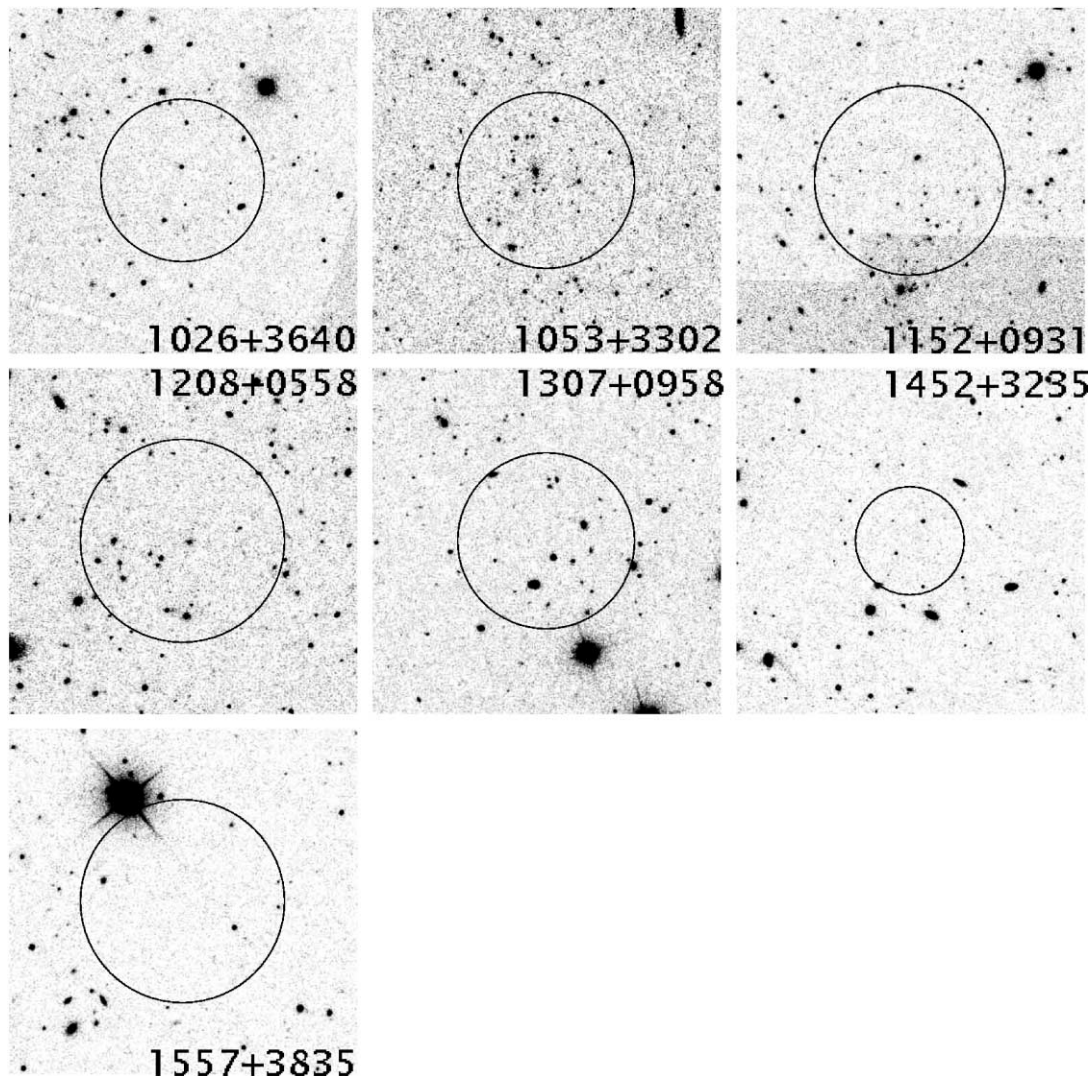

Fig. 2.—SDSS composite g, r, i images of candidate fields that did not survive the cluster-detecting stage of our algorithm. The orientation and scale are the same as in Fig. 1. The brightest object in any of the 4p.e. error circles is $g = 19.35$ mag; for most fields the brightest object is $g > 21.0$. Rutledge et al. (2003) identified IRXS J145234.9+323536 as a candidate INS, but no X-ray source was detected by their follow-up *Chandra* observations.
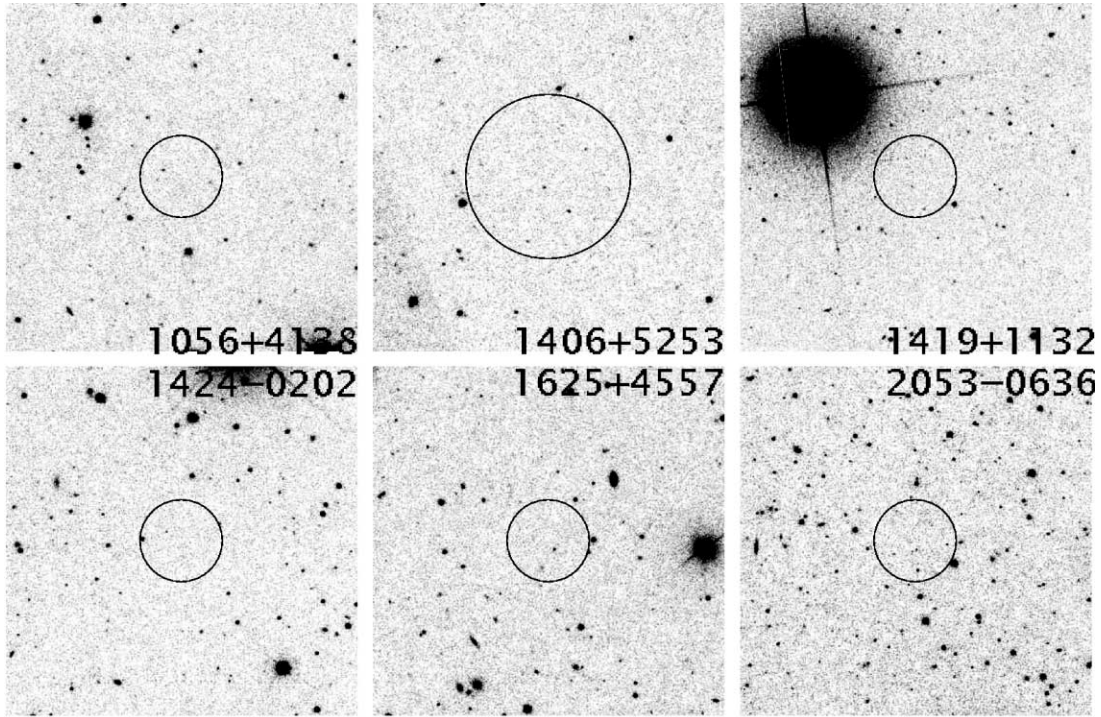
Fig. 3.—SDSS composite g, r, i images of six fields that did not survive our final version of the algorithm but may host interesting X-ray emitters. The orientation and scale are the same as in the previous figures. The brightest object in any of the 4p.e. error circles is $g = 22.08$ mag.

TABLE 2
X-Ray and Optical Data for Seven Cluster Candidates, Plus Six Other Interesting Fields

		ROSAT			SDSS	
Source Name: 1RXS J	1σ (arcsec)	Count Rate (10^{-2} counts s^{-1})	Detection Likelihood	Exposure Time (s)	g-magnitude	Minimum $\log(f_X/f_g)$
Seven Cluster Candidates						
102659.6+364039	12	6.1 ± 1.6	26	371	20.43	1.3
105352.5+330255	13	3.0 ± 1.1	15	384	21.05	1.3
115247.0+093118	14	2.8 ± 1.1	13	433	21.51	1.4
120844.3+055839	15	2.9 ± 1.2	11	410	21.50	1.4
130723.7+095801	13	14.2 ± 2.6	47	303	19.35	1.3
145234.9+323536[a]	8	8.0 ± 1.3	74	614	21.52	1.9
155705.0+383509	15	3.0 ± 1.4	9	272	21.12	1.3
Other Interesting Fields						
105648.6+413833[b]	6	1.6 ± 0.7	7	413	22.40	1.5
140654.5+525316	12	1.3 ± 0.6	10	617	22.50	1.5
141944.5+113222	6	2.2 ± 1.1	7	288	24.70	2.6
142423.3−020201	6	2.6 ± 1.1	8	322	22.08	1.6
162526.9+455750[b]	6	1.4 ± 0.6	7	572	22.26	1.4
205334.0−063617[b,c]	6	2.1 ± 0.8	9	434	23.16	1.9

[a] Identified as a candidate INS by Rutledge et al. (2003). No source detected by *Chandra* (Rutledge et al. 2003).
[b] Cataloged X-ray positional error appears to be an underestimate.
[c] Outside of optical cluster catalog footprint.

a spectrum for this star with the APO 3.5 m telescope; it appears to be a late G/early K star with no emission. G/K stars typically have (log) flux ratios between -4.3 and -1.5 (Stocke et al. 1991), while this star has $\log(f_X/f_g) = -1.11$ and is therefore unlikely to be the X-ray source.

APPENDIX A2

OTHER INTERESTING FIELDS

Three of these six fields meet all of our selection criteria (1RXS J105648.6+413833, 1RXS 162526.9+455750, and 1RXS J205334.0$-$063617). However, the RASS images of these fields, along with their count rates and exposure times, suggest that their cataloged positional error of $6''$ is an underestimate. They cannot therefore be considered among our best INS candidates. The other three fields were identified in preliminary work as possibly hosting interesting X-ray sources. Below we provide additional information about one of the $6''$ fields, and we describe why the three "early" fields were eliminated but remain interesting.

1RXS J105648.6+413833: A known $g = 19.86$ quasar, QORG J105651.3+413809, is $39''$ (6.4 times the quoted RASS positional error) from the X-ray position (Flesch & Hardcastle 2004); it is also the radio source FIRST J105651.2+413809. While this quasar has $\log(f_X/f_g) = 0.53$, within the range for AGNs (Stocke et al. 1991), such a large positional offset relative to the quoted positional error means that this quasar is unlikely to be a RASS source, unless the quoted X-ray positional error is underestimated.

A *Galaxy Evolution Explorer* (Martin et al. 2005; Morrissey et al. 2005) source with a near-ultraviolet magnitude of 21.85 ± 0.29 is positionally coincident ($1''$) with a $g = 22.67$ SDSS source within the 4p.e. error circle. The nature of this object, SDSS J105649.58+413837, is difficult to determine from its SDSS photometry because of its faintness ($u = 23.9$, $g = 22.7$) and resulting uncertainties in its optical colors.

1RXS J140654.5+525316: This field was eliminated because of a $g = 21.70$, $\log(f_X/f_g) = 1.16$ object offset from the RASS source by between 3 and 4 times the quoted positional error. However, this object's photometry is suspect and its colors are inconsistent ($u - g = 3.5 \pm 2.5$) with that of a typical AGN.

1RXS J141944.5+113222: This field was eliminated when the X-ray images of our fields were examined: it cannot be completely ruled out that this X-ray source and its neighbor, the bright star 1RXS J141949.0+113619, are actually the same source. While it meets all of our algorithm's other criteria, we therefore include it in this list rather than among our INS candidates.

1RXS J142423.3$-$020201: This field was eliminated by our algorithm because of the presence of a $g = 20.65$ object with $\log(f_X/f_g) = 1.05$ about 4p.e. from the RASS position. We obtained several spectra of this object with the 3.5 m telescope at APO. These spectra indicate that the object is most likely an ordinary G star with no signs of emission and that it is therefore unlikely to be the X-ray source. The next brightest SDSS object within the 4p.e. error circle is $g = 22.08$, so the counterpart to the X-ray source would then have $\log(f_X/f_g) \geq 1.6$.

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