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National Aeronautics and Space Administration

ROSAT

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Title of Research: **"EGRET Sources at Intermediate Galactic Latitudes"**

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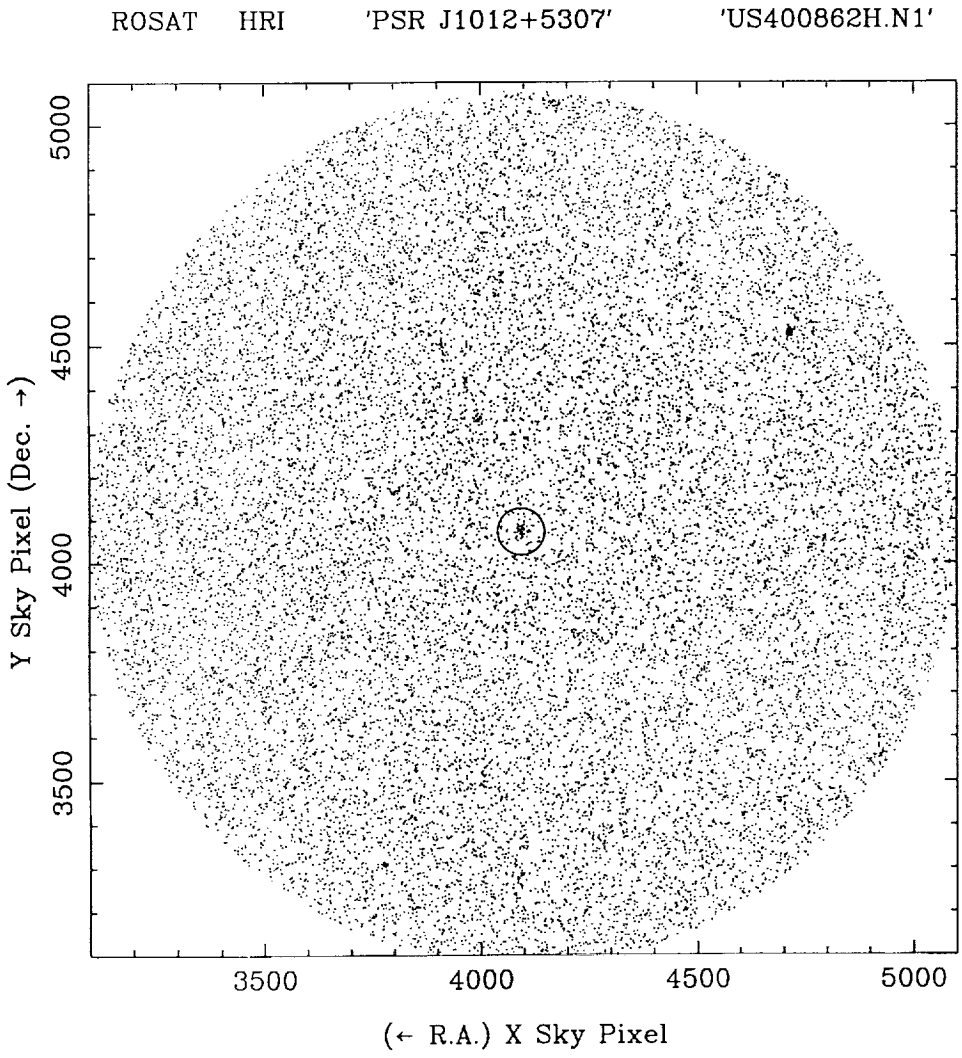
SUMMARY

During the period 15 March 1992 through 31 October 1997, 12 papers using *ROSAT* data, supported in part by this grant, were published in refereed journals, and one paper was published in a conference proceedings. Their bibliographical references are listed in the Appendix, and the abstracts of these papers are given in the next 13 sections of this report. Finally, a summary of the work completed to date on the newest project, for which *ROSAT* data are still being received, is given in the section entitled "EGRET Sources at Intermediate Galactic Latitude".



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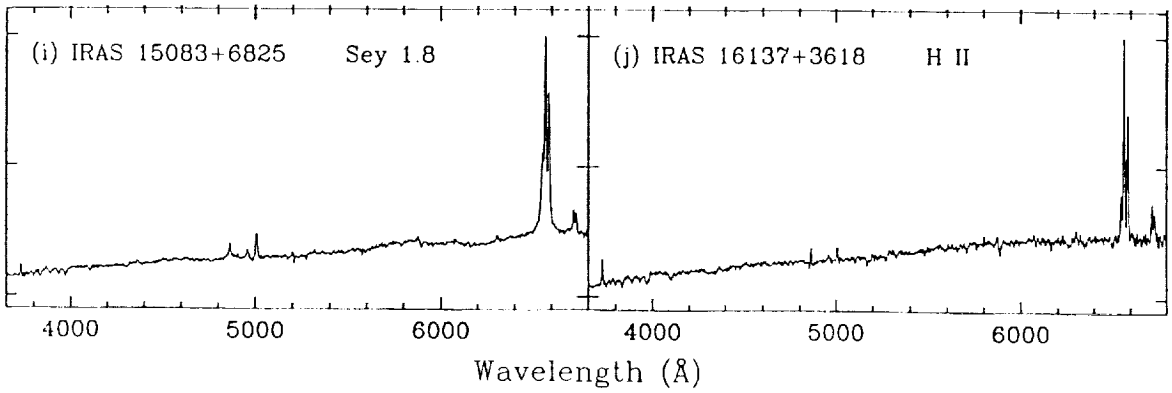
1. The True Nature of *IRAS*–Selected X-ray–Luminous "Normal" Galaxies in the *ROSAT* All-Sky Survey

E. C. Moran, J. P. Halpern, and D. J. Helfand

Luminous star-forming galaxies have often been suggested as potentially significant contributors to the cosmic X-ray background (XRB). Interest in this possibility has been rekindled by a recently published sample of 244 *ROSAT/IRAS* galaxies that includes 20 with extreme X-ray luminosities ($L_X = 10^{42-44}$ ergs s^{-1}) that are claimed to be "normal" spiral galaxies. To investigate whether or not these 20 X-ray luminous spirals are truly normal star-forming galaxies, we have rexamined their classifications by obtaining new optical spectra of 13 of them, and by locating spectra in the literature for four. Our results indicate that 13 of the 17 objects are previously unrecognized Seyfert galaxies. Of the four star-forming non-Seyfert galaxies found in this sample, three are incorrectly identified as X-ray sources. Only one H II galaxy is a confirmed X-ray source, but it has $L_X \approx 10^{42}$ ergs s^{-1} and is only about twice as luminous as the most luminous normal spirals detected previously at X-ray wavelengths. Thus, there are no H II galaxies with L_X substantially in excess of 10^{42} ergs s^{-1}, and claims of a new class of X-ray-luminous spiral galaxies are not supported by this study.

Subject headings: galaxies:active – galaxies: Seyfert – infrared: galaxies – X-rays: galaxies



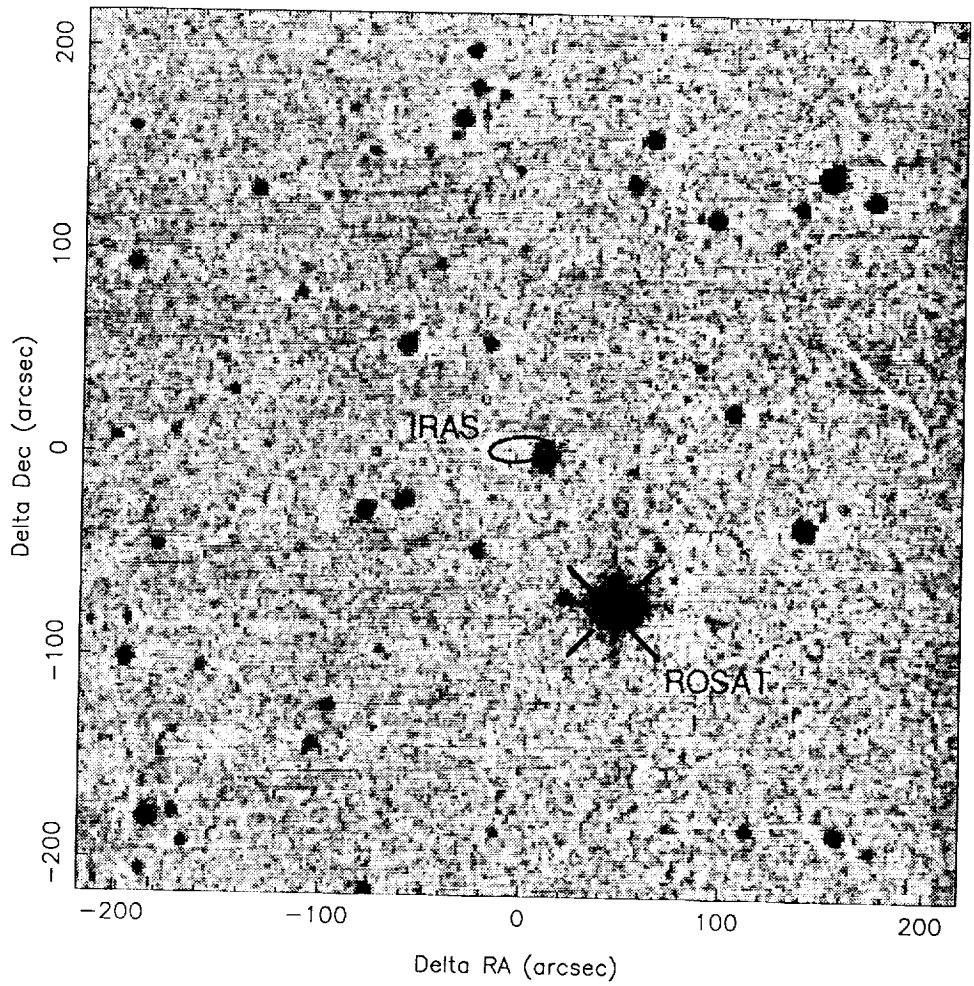


FIG. 2.—Optical finding chart for IRAS 16137+3618, made from the digitized POSS plates at STScI, with the *IRAS* error ellipse (95%) and the position of the RASS source marked (*cross*). The bright star (m_V = 10.06) coincident with the RASS position—not the H II *IRAS* galaxy—is virtually certain to be the X-ray source in this case. The *IRAS* error ellipse is centered at $\alpha_{2000} = 16^h15^m35\overset{s}{.}8$, $\delta_{2000} = +36°10'48''$.

2. NO X-RAY–LUMINOUS STARBURSTS IN THE *EINSTEIN* MEDIUM SENSITIVITY SURVEY, EITHER

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ABSTRACT

We continue to investigate recurrent claims that a substantial number of "normal" star-forming galaxies may have X-ray luminosities in the range 10^{42-44} ergs s^{-1}. In this installment, we present new spectra of four such emission-line galaxies that were ambiguously classified in the *Einstein* Extended Medium Sensitivity Survey (EMSS), and find that they all have intermediate-type Seyfert nuclei as evidenced by broad components of their Hα lines. We argue that any of the remaining emission-line galaxies in the EMSS with $10^{42} < L_X < 10^{44}$ ergs s^{-1} that were flagged as needing further spectroscopic work are almost certain to have active nuclei as well. We conclude that in these as well as other samples of X-ray-selected emission-line galaxies, X-ray luminosities in excess of 10^{42} ergs s^{-1} can and should be attributed to an active nucleus, even in the case that most of the infrared continuum or optical emission-line luminosity is caused by star formation. There is as yet no good evidence for X-ray-luminous starbursts.

Subject headings: galaxies:active – galaxies: Seyfert – galaxies: starburst – X-rays: galaxies

3. A POSSIBLE X-RAY DETECTION OF THE BINARY MILLISECOND PULSAR J1012+5307

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ABSTRACT

A possible X-ray detection of the newly discovered binary millisecond radio pulsar PSR J1012+5307 was obtained from an archival *ROSAT* observation. The 80 ± 24 photons detected correspond to a 0.1–2.4 keV luminosity of $\approx 2.5 \times 10^{30}$ ergs s^{-1} at the nominal dispersion-measure distance of 520 pc. This luminosity is a factor of 2 less than that of PSR J0437–4715, a near twin of PSR J1012+5307 in its spin parameters and energetics, and the only millisecond pulsar from which pulsed X-rays have definitely been detected. PSR J1012+5307 is also within 6° of the "HI hole" in Ursa Major, providing a new estimate of the electron column density through this region which confirms that the ionized column density is also low. The small neutral column density to PSR J1012+5307, $N_{\rm H} < 7.5 \times 10^{19}$ cm^{-2}, will facilitate future soft X-ray study, which will help to discriminate between thermal and nonthermal origins of the X-ray emission in millisecond pulsars.

Subject headings: pulsars: individual (J1012+5307) – stars: neutron – X-rays: stars

4. X-RAY SPECTRA OF CATACLYSMIC VARIABLES FROM *ROSAT*

H. R. RICHMAN

For 37 disk-accreting cataclysmic variables (CVs) observed with the *ROSAT* Position Sensitive Proportional Counter, we determine X-ray spectral parameters and the orbital dependence thereof. The raw data are fitted with an optically thin, thermal bremsstrahlung model plus absorption. We obtain average values for the temperature $kT \sim 2.4$ keV and column densities $N_{\rm H} \sim 5 \times 10^{20}$ cm^{-2}. Estimated 0.1–2.4 keV fluxes are in the range log $F_{\rm X} = -13.5$ to -11 ergs cm^{-2} s^{-1}. Systematic excesses in the residuals of the fitted spectra near $E = 0.2$ and 0.8 keV suggest that the X-ray emission in CVs is not well described by this single-temperature model.

Changes in softness ratio as a function of orbital phase are seen in 17 of the 37 CVs. Our results typically exhibit a decrease in the 0.1–0.4 keV flux near orbital phases $\phi = 0.1$ and $\phi = 0.5$. Variability in spectral hardness on several timescales is seen in three systems.

We address the problem of understanding the observed 0.1–2.4 keV emission. We show that the ratio of X-ray flux to visual flux correlates with accretion rate, absolute visual magnitude, and equivalent width of the Hβ emission line. The results are consistent with the X-rays originating in the boundary layer between the accretion disk and the white dwarf. A coronal contribution from the companion to the X-ray luminosity is rejected because the luminosities found are above the saturation boundary in $L_{\rm X}$ determined for late-type main sequence stars.

Subject headings: novae, cataclysmic variables – radiation mechanisms: nonthermal – X-rays: stars

5. SOFT X-RAY PROPERTIES OF THE BINARY MILLISECOND PULSAR J0437–4715

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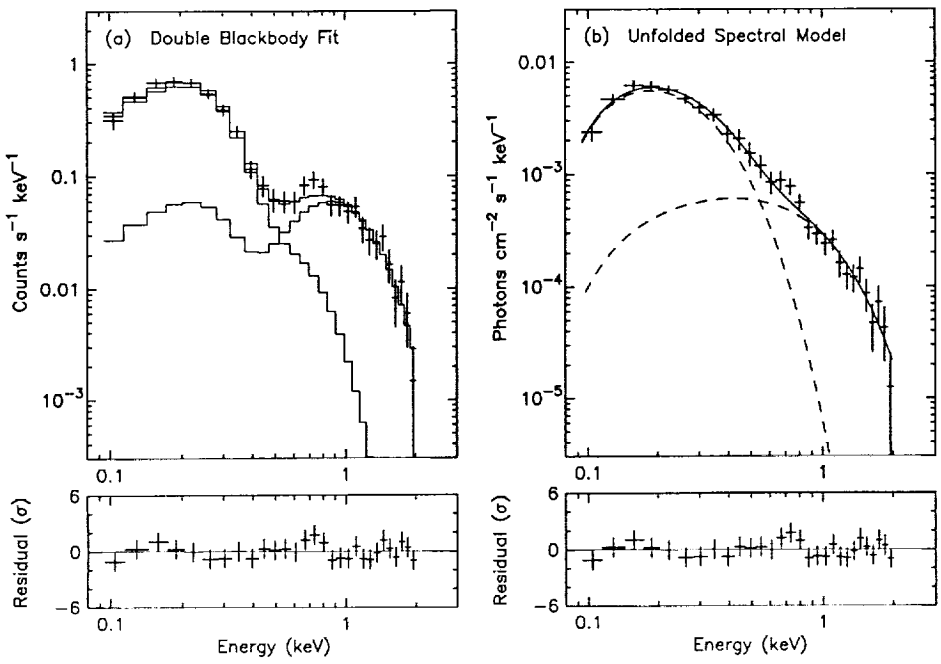
ABSTRACT

We obtained a light curve for the 5.75 ms pulsar J0437–4715 in the 65–120 Å range with 0.5 ms time resolution using the Deep Survey instrument on the *EUVE* satellite. The single-peaked profile has a pulsed fraction of 0.27 ± 0.05, similar to the *ROSAT* data in the overlapping energy band. A combined analysis of the *EUVE* and *ROSAT* data is consistent with a power-law spectrum of energy index $\alpha = 1.2 - 1.5$, intervening column density $N_{\rm H} = (5 - 8) \times 10^{19}$ cm^{-2}, and luminosity 5.0×10^{30} ergs s^{-1} in the 0.1–2.4 keV band. We also use a bright *EUVE/ROSAT* source only 4′.2 from the pulsar, the Seyfert galaxy RX J0437.4–4711 (= EUVE J0437–471 = 1ES 0435–472), to obtain an independent upper limit on the intervening absorption to the pulsar, $N_{\rm H} < 1.2 \times 10^{20}$ cm^{-2}.

Although a blackbody spectrum fails to fit the *ROSAT* data, two-component spectral fits to the combined *EUVE/ROSAT* data are used to limit the temperatures and surface areas of thermal emission that might make *partial* contributions to the flux. A hot polar cap of radius 50−600 m and temperature $(1.0-3.3)\times10^6$ K could be present. Alternatively, a larger region with $T = (4 - 12) \times 10^5$ K and area less than 200 km^2, might contribute most of the *EUVE* and soft X-ray flux, but only if a hotter component were present as well. Any of these temperatures would require some mechanism(s) of surface reheating to be operating in this old pulsar, the most plausible being the impact of accelerated electrons and positrons onto the polar caps. The kinematically corrected spin-down power of PSR J0437–4715 is only 4×10^{33} ergs s^{-1}, which is an order of magnitude less than that of the lowest-luminosity γ-ray pulsars Geminga and PSR B1055–52. The absence of high-energy γ-rays from PSR J0437–4715 might signify an inefficient or dead outer gap accelerator, which in turn accounts for the lack of a more luminous reheated surface such as those intermediate-age γ-ray pulsars may have.

Subject headings: pulsars: individual (PSR J0437–4715) – stars: neutron – X-rays: stars



6. A LONG *EUVE* OBSERVATION OF THE SEYFERT GALAXY RX J0437.4–4711

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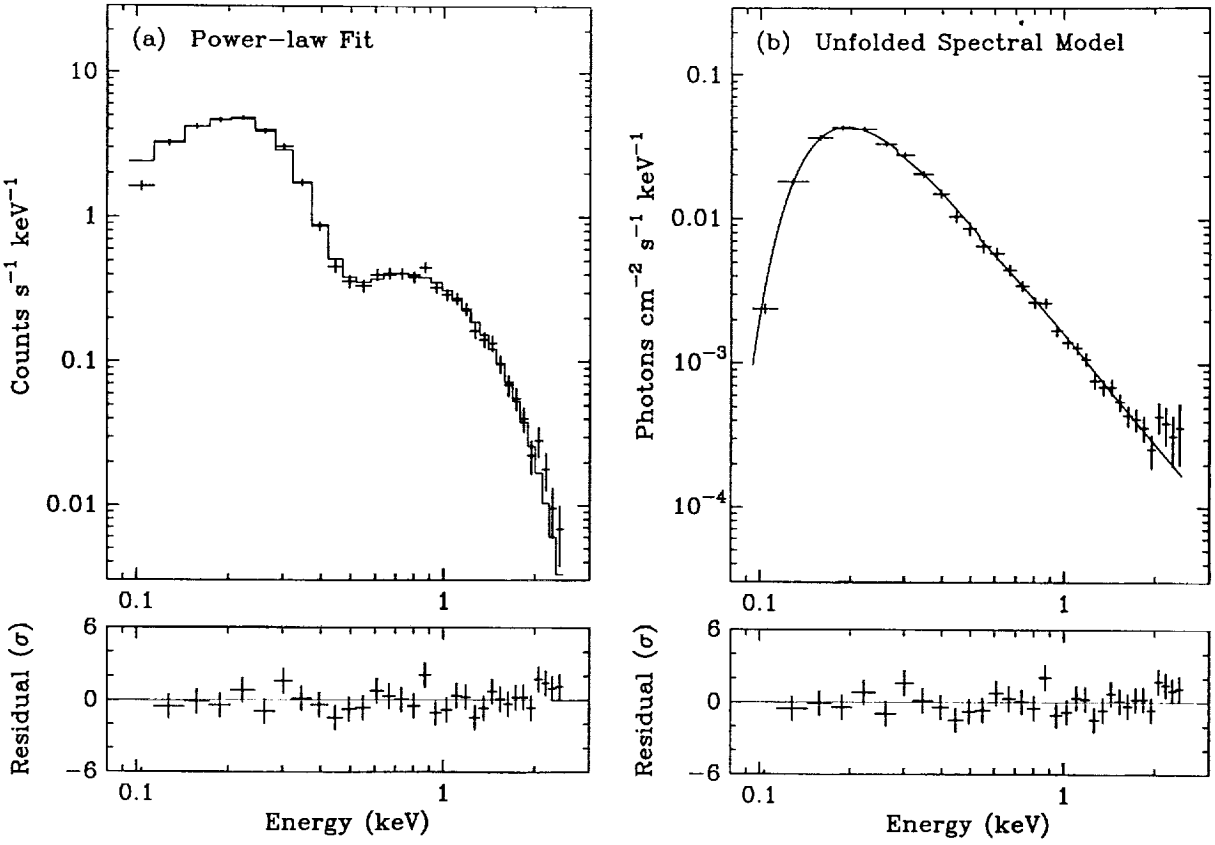
ABSTRACT

We monitored the soft X-ray-selected Seyfert galaxy RX J0437.4–4711 with the *EUVE* satellite continuously for 20 days in 1994 October-November. The Seyfert was detected in the 70–110 Å range, both in the short-wavelength spectrometer and in the Deep Survey imager. Its light curve shows large-amplitude variability by a factor of 4 over the 20 day period, and a minimum doubling time of 5 hr. Its power spectrum in the frequency range $10^{-6.0}$ to $10^{-4.1}$ Hz is fitted by a power law of slope -1.25 ± 0.25. A possible period of 0.906 ± 0.018 days is also apparent in the light curve and power spectrum. This is a timescale that might correspond to orbital motion in the inner accretion disk around a $\sim 10^8\, M_\odot$ black hole. The divergence of the power at low frequencies indicates that even longer observations in the EUV would be necessary to characterize the variability of the bulk of the Seyfert luminosity. The *ROSAT* PSPC spectrum from a pointed observation of RX J0437.4–4711 in 1992 September is well fitted by a power law of energy index $\alpha = 1.56 \pm 0.09$ and $N_{\rm H} = (1.01 \pm 0.16) \times 10^{20}$ cm^{-2}. The *EUVE* spectrum is consistent

with these parameters and shows no evidence of emission lines. We also present an *IUE* spectrum that reveals a flat continuum in νf_ν, and a Lyα line at $z = 0.052$ with FWHM $\approx$ 4000 km s^{-1}. In all of its properties, RX J0437.4–4711 appears to be an ordinary Seyfert 1 galaxy.

Subject headings: galaxies: active – galaxies: individual (RX J0437.4–4711) – galaxies: Seyfert – ultraviolet: galaxies – X-rays: galaxies



7. *ROSAT* PSPC and HRI Observations of the Composite Starburst/Seyfert 2 Galaxy NGC 1672

W. N. BRANDT, J. P. HALPERN, AND K. IWASAWA

ABSTRACT

The nearby barred spiral galaxy NGC 1672 is thought to have a weak Seyfert nucleus in addition to its strong starburst activity. Observations with the Position Sensitive Proportional Counter (PSPC) and High Resolution Imager (HRI) instruments on board the *ROSAT* X-ray satellite show that three X-ray sources with luminosities $(1-2)\times10^{40}$ ergs s^{-1} are clearly identified with NGC 1672. The strongest X-ray source lies at the nucleus, and the other two lie near the ends of the prominent bar, locations that are also bright in Hα and near-infrared images. The nuclear source is resolved by the HRI on about the scale of the recently identified nuclear ring, and one of the sources at the ends of the bar is also probably resolved. The X-ray spectrum of the nuclear source is quite soft, having a Raymond-Smith plasma temperature of ≈ 0.7 keV and little evidence for intrinsic absorption. The *ROSAT* band X-ray flux of the nuclear source appears to be dominated not by X-ray binary emission but rather by diffuse gas emission. While the properties of the nuclear source are generally supportive of a superbubble interpretation, its large density and emission measure stretch the limits that can be comfortably accommodated by such models. We do not detect direct emission from the putative Seyfert nucleus, although an alternative model for the nuclear source is thermal emission from a gas that is photoionized by a hidden Seyfert nucleus. The spectra of the other two X-ray sources are harder than that of the nuclear source, and superbubble models for them have the same strengths and weaknesses.

Key words: galaxies: individual: NGC 1672 – galaxies: individual: NGC 1688 – galaxies: Seyfert – X-rays: galaxies

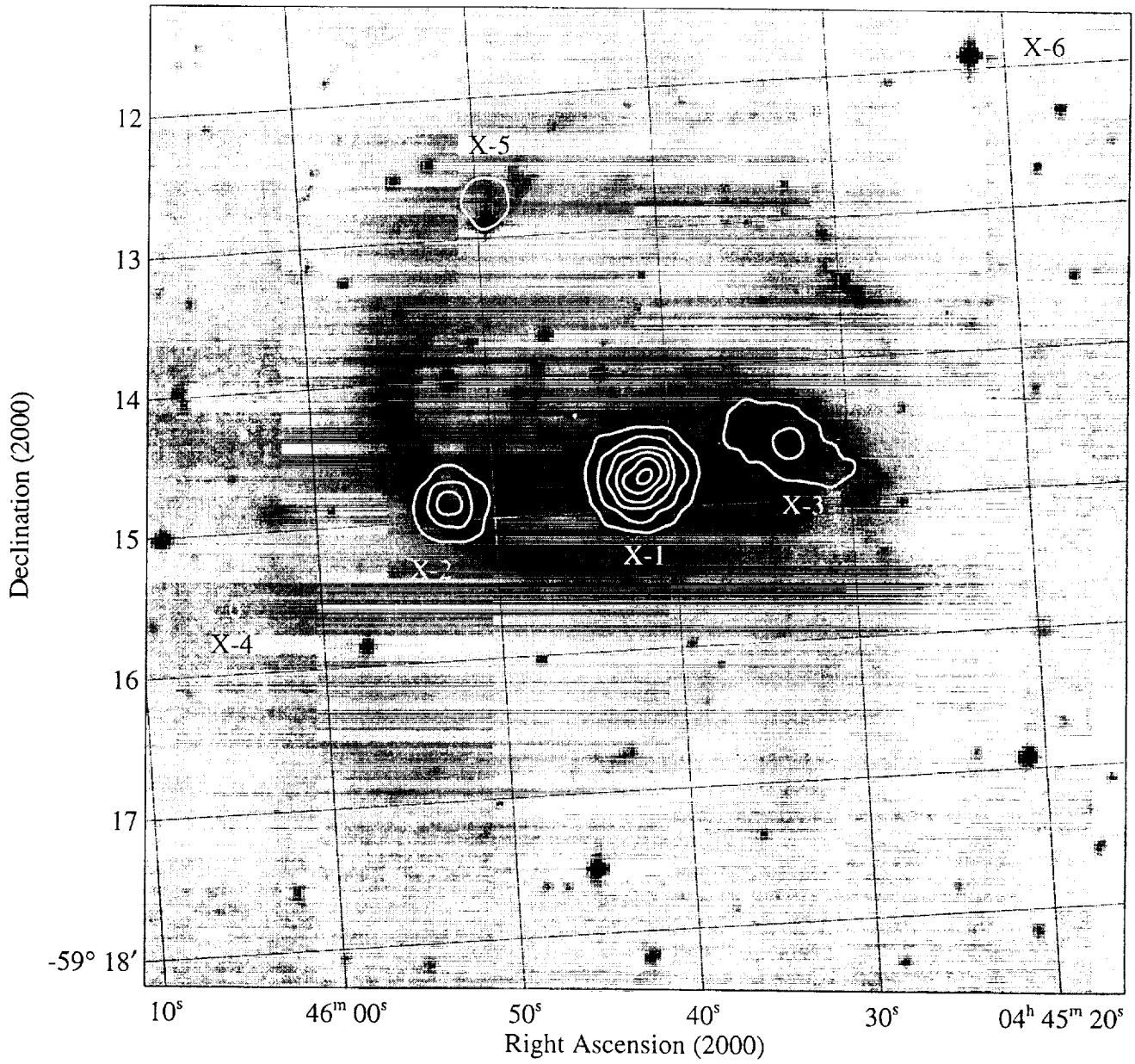


Figure 1. Contours of the adaptively smoothed HRI image overlaid on the image of NGC 1672 from the UK Schmidt southern sky survey J plate. Contours are at 5.3, 9.2, 16.0, 27.8, 48.4 and 84.1 per cent of the maximum pixel value (see the text for absolute source fluxes). Note the strong central X-ray source and the locations of X-ray sources near both ends of the bar.

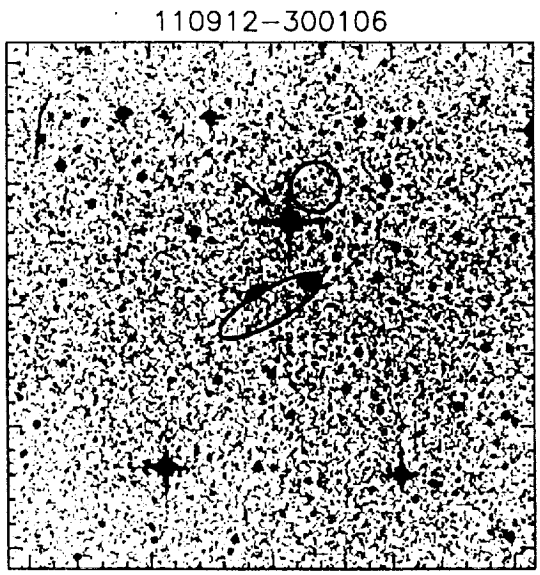
8. Classification of *IRAS*-Selected X-ray Galaxies in the *ROSAT* All-Sky Survey

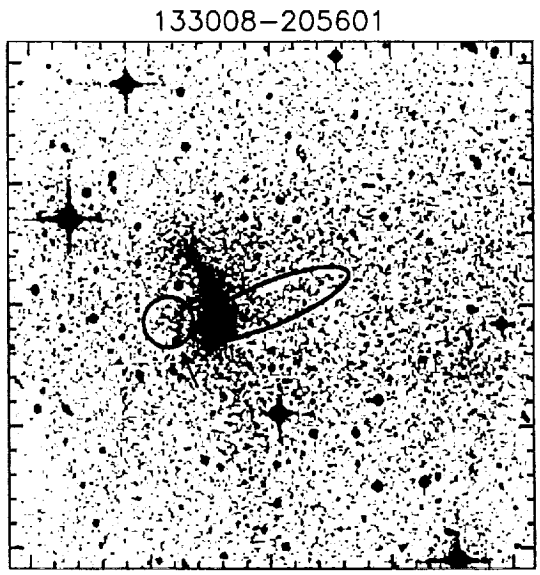
E. C. Moran, J. P. Halpern, and D. J. Helfand

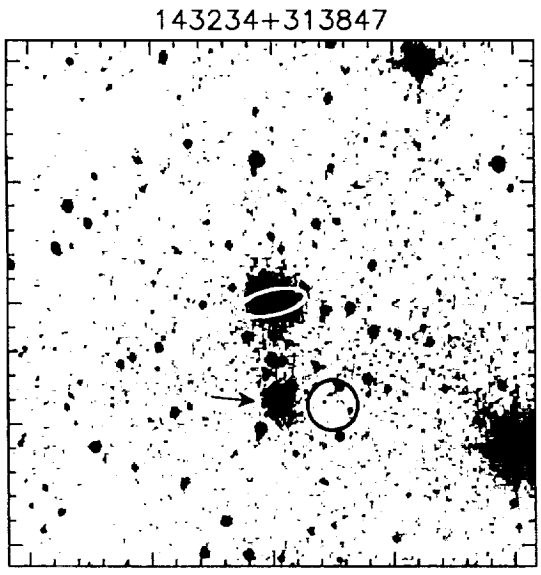
To explore the possibility that star-forming galaxies or obscured Seyfert galaxies, both of which are known to be luminous infrared sources, contribute significantly to the cosmic X-ray background, we have carried out an extensive program to obtain accurate spectroscopic classifications of the Boller et al. (1992) catalog of *IRAS* sources detected in the *ROSAT* All-Sky Survey. This has involved careful optical spectroscopy, a review of the literature, and efforts to reveal the contaminants in the sample. Classifications have been determined for 210 of the 241 X-ray sources in the catalog; 105 are presented here for the first time. A large number of IR/X-ray source chance coincidences are found in this sample; of the 40–50 expected, we have firmly identified 18 and have established strong cases for 29 others. Most chance coincidences involve bright stars or Seyfert galaxies close (in projection) to IR-bright H II galaxies. Although this work was initially motivated by the report that a new class of X-ray–luminous, normal spiral galaxies was to be found in this sample, we find no evidence for such a class. Most of the extragalactic X-ray sources are active galactic nuclei (AGNs), consistent with the results of previous studies of X-ray–selected objects. However, many of these AGNs exhibit weak or heavily reddened Seyfert features in their optical spectra. In addition, two rare types of AGNs are found in this sample with surprising frequency: I Zw 1 objects (also called narrow-line Seyfert 1s) and starburst/Seyfert composite galaxies, a new class of luminous X-ray sources. We have shown that the Boller et al. object 202103–223434 (= *IRAS* 20181–2244), reported to be the best example of a narrow-line quasar, is actually a member of the I Zw 1 class. The enigmatic starburst/Seyfert composite galaxies have optical spectra dominated by the features of H II galaxies, yet X-ray luminosities typical for Seyfert galaxies. Close examination of their optical spectra reveals subtle Seyfert signatures: O [III] lines broader

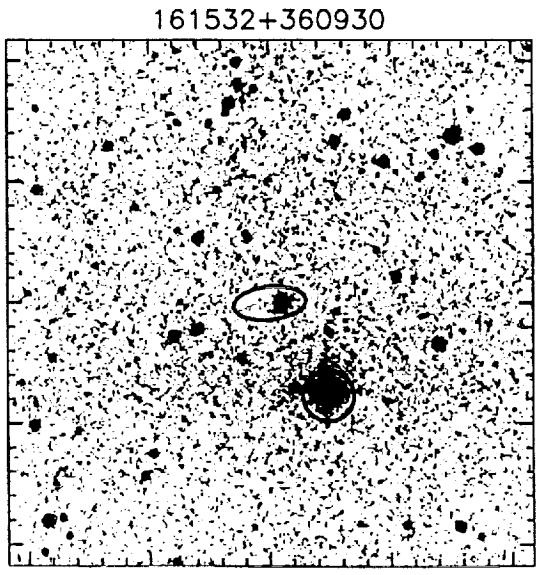
than all other lines in the spectrum and, in some cases, a weak, broad H α component. Obscuration of the active nucleus is likely to explain the X-ray and optical properties of these objects. We describe a scenario in which such optically innocuous, obscured AGNs could comprise an important new component of the X-ray background.

Subject headings: galaxies:active – galaxies: Seyfert – infrared: galaxies – X-rays: galaxies







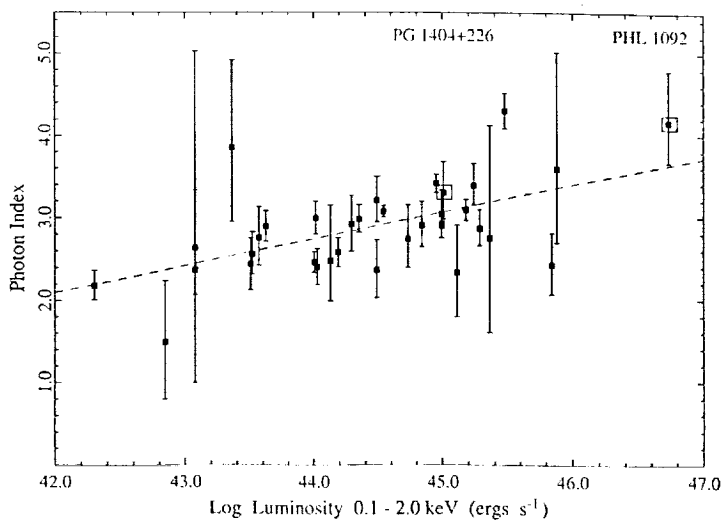


9. Extreme X-ray Variability In The Narrow-Line QSO PHL 1092

KARL FORSTER AND JULES P. HALPERN

A *ROSAT* observation of the narrow-line Fe II QSO PHL 1092 shows rapid variability that requires an efficiency of at least 0.13, exceeding the theoretical maximium for an accretion disk around a non-rotating black hole. Plausible explanations for its high efficiency incorporate anisotropic emission and/or accretion onto a rapidly rotating black hole, the latter recently suggested by Kwan et al. as a mechanism for generating PHL 1092's strong Fe II lines by mechanical heating in an accretion disk. The soft X-ray luminosity of PHL 1092 had also increased by a factor of 21 over the weak *Einstein* detection, to more than 5×10^{46} ergs s^{-1}. Its photon spectral index of 4.2 is among the steepest of any AGN. These X-ray properties are characteristic of narrow-line Seyfert 1 galaxies, of which PHL 1092 is evidently a very luminous member. Narrow-line QSOs also extend a significant correlation between X-ray luminosity and X-ray spectral index which we have found among a large sample of optically-selected, narrow-line Seyfert 1 galaxies observed by *ROSAT*.

Subject headings: quasars: individual (PHL 1092, PG 1404+226) – X-rays: galaxies



10. THE GEMINGA PULSAR: SOFT X-RAY VARIABILITY AND AN *EUVE* OBSERVATION

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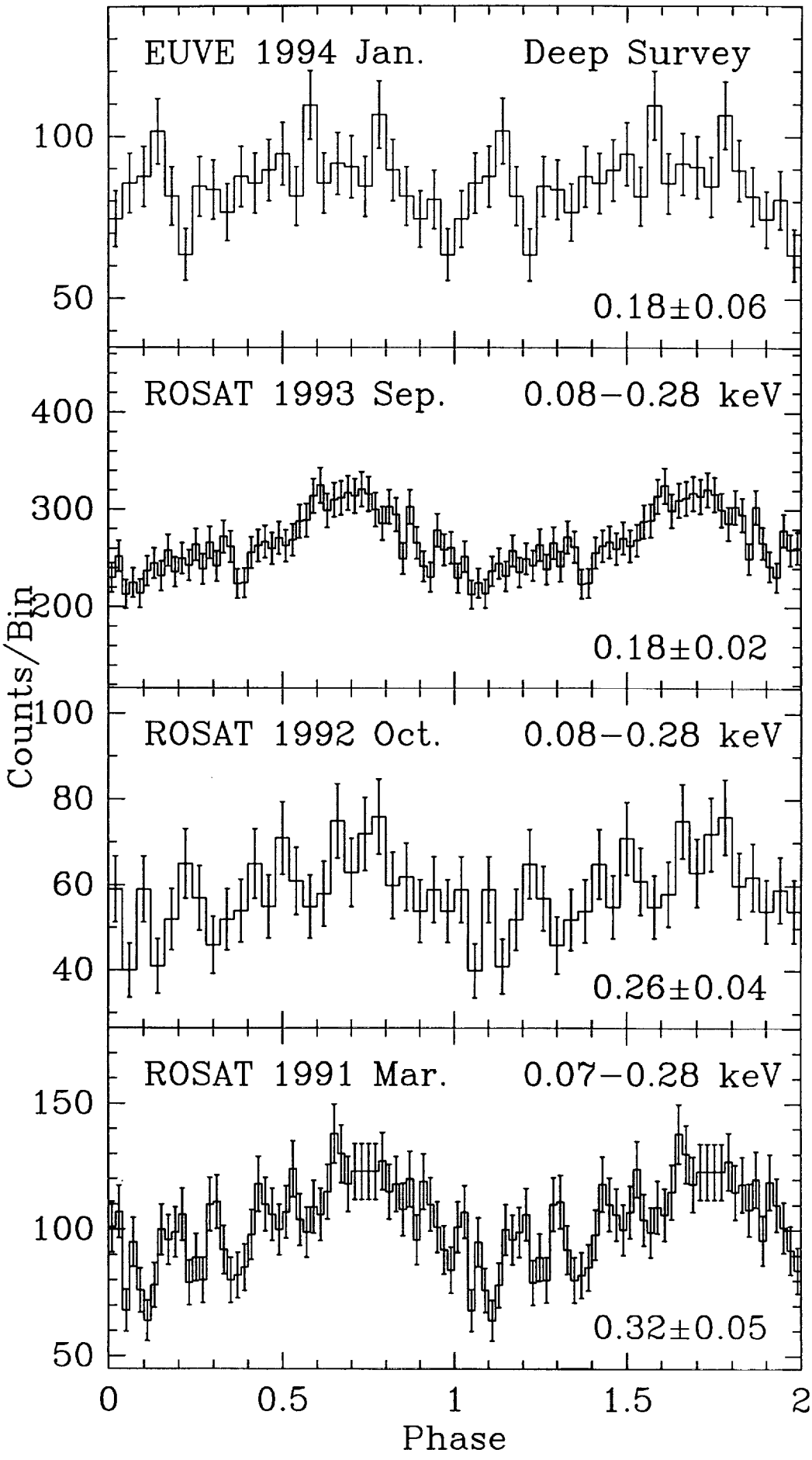
ABSTRACT

We observed the Geminga pulsar with the *EUVE* satellite, detecting pulsed emission in the Deep Survey imager. Joint spectral fits of the *EUVE* flux with *ROSAT* PSPC data are consistent with thermal plus power-law models in which the thermal component makes the dominant contribution to the soft X-ray flux seen by *EUVE* and *ROSAT*. The data are consistent with blackbody emission of $T = (4 - 6) \times 10^5$ K over most of the surface of the star at the measured parallax distance of 160 pc. Although model atmospheres are more realistic, and can fit the data with effective temperatures a factor of 2 lower, current data would not discriminate between these and blackbody models. We also find evidence for variability of Geminga's soft X-ray pulse shape. Narrow dips in the light curve that were present in 1991 had largely disappeared in 1993/1994, causing the pulsed fraction to decline from 32% to 18%. If the dips are attributed to cyclotron resonance scattering by an $e^{\pm}$ plasma on closed magnetic field lines, then the process that resupplies that plasma must be variable.

Subject headings: pulsars: individual (Geminga) – stars: neutron – X-rays: stars


EUVE 1994 Jan.
Deep Survey
0.18±0.06
ROSAT 1993 Sep.
0.08−0.28 keV
0.18±0.02
ROSAT 1992 Oct.
0.08−0.28 keV
0.26±0.04
ROSAT 1991 Mar.
0.07−0.28 keV
0.32±0.05
Counts/Bin
Phase
100
50
400
300
200
100
80
60
40
150
100
50
0
0.5
1
1.5
2

11. A BROAD-BAND X-RAY STUDY OF THE GEMINGA PULSAR

J. P. HALPERN AND F. Y.-H. WANG

We present a comprehensive study of the Geminga pulsar at energies 0.1–10 keV using data from the *ASCA*, *ROSAT*, and *EUVE* satellites. The bulk of the soft X-ray flux can be parameterized as a blackbody of $T = (5.6 \pm 0.6) \times 10^5$ K, occupying a fraction 0.10–0.64 of the surface area of the neutron star at the parallax distance of 160 pc. The *ASCA* detection of Geminga resolves the nature of the harder X-ray component previously discovered by *ROSAT* in favor of nonthermal emission, rather than thermal emission from a heated polar cap. The hard X-ray spectrum can be fitted by a power-law of energy index 1.0 ± 0.5. The hard X-ray light curve has a strong main peak and a weak secondary peak; its total pulsed fraction is $\approx 55\%$. Three *ROSAT* PSPC observations show significant variability of Geminga's light curve. In particular, a peculiar energy dependence of the modulation in the soft X-ray component, dubbed the "Geminga effect" in the original PSPC data, is not present in later observations. In addition, fine structure in the soft X-ray light curve, interpreted as eclipses due to cyclotron resonance scattering by a plasma screen on the closed magnetic field lines, almost disappeared in the most recent observations. All of the variable properties of Geminga can probably be associated with the nonthermal process that supplies $e^{\pm}$ pairs to its inner magnetosphere.

Subject headings: pulsars: individual (Geminga) – stars: neutron – X-rays: stars

12. E 0336–248 : A NEW BL LAC OBJECT FOUND BY AN OLD *EINSTEIN*

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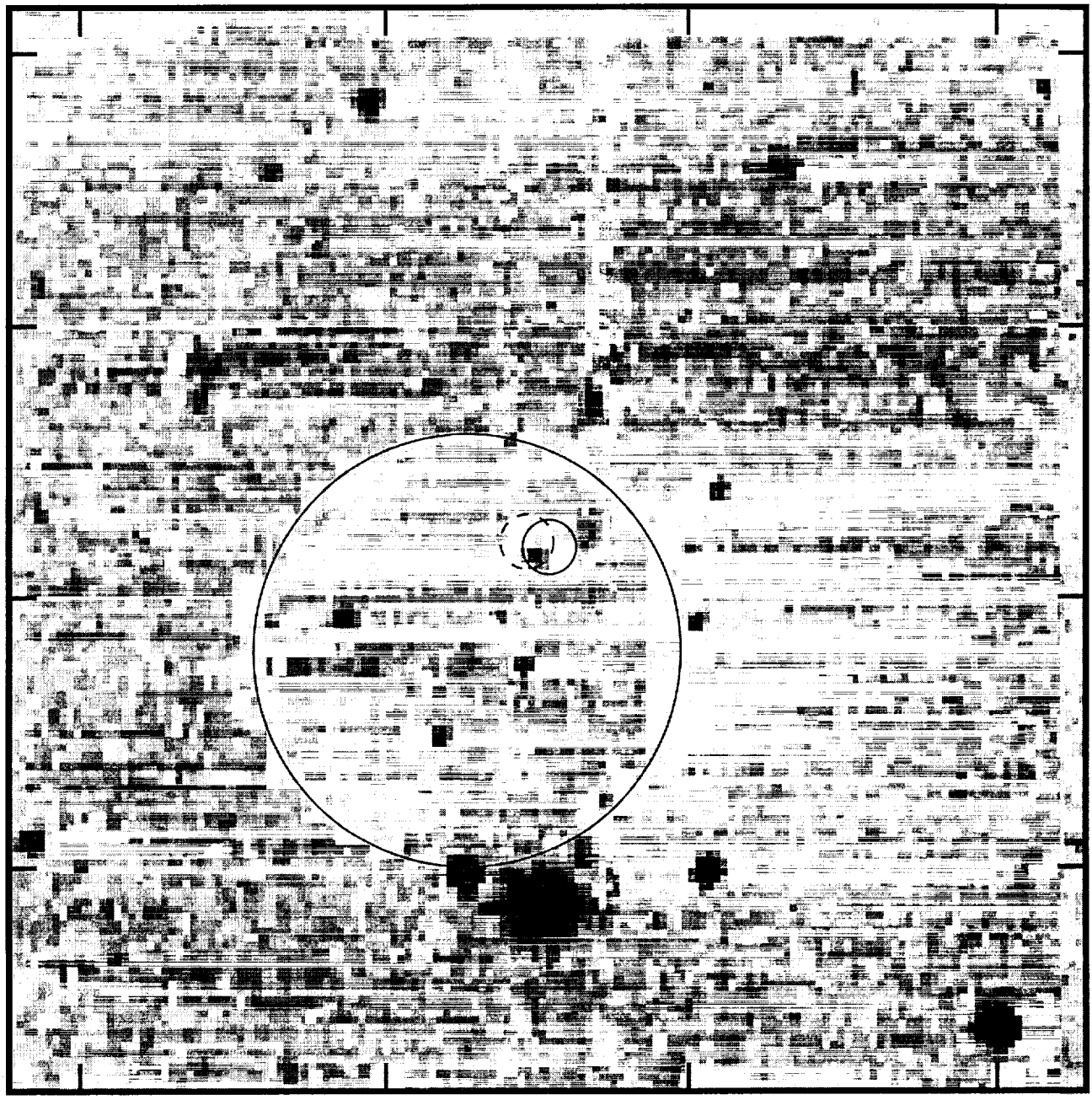
ABSTRACT

We obtained new *ROSAT* HRI and optical observations in the field of the *Einstein* X-ray source E 0336–248, which we use to identify it as a 19th magnitude BL Lacertae object at $z = 0.251$ with $L_X = 1 \times 10^{45}$ erg s^{-1}. It is also a 14 mJy radio source at 20 cm. An emission-line galaxy at $z = 0.043$ that was previously considered a Seyfert identification for E 0336–248 is shown instead to be an unrelated, non-active H II region galaxy that lies 78″ from the X-ray source. The resolution of this historical case of mistaken identity illustrates that discoveries of non-AGN emission-line galaxies with high X-ray luminosity should be tested carefully. The properties of E 0336–248 are similar to those of other X-ray selected BL Lacs, including its location in an apparent group or cluster of galaxies. Somewhat unusual is the weak contribution of nonstellar optical light relative to the starlight in the spectrum of its host galaxy, which raises once again the possibility that even high-luminosity BL Lac objects may be difficult to identify in X-ray selected samples. We discuss a possible manifestation of this problem that appeared in the recent literature.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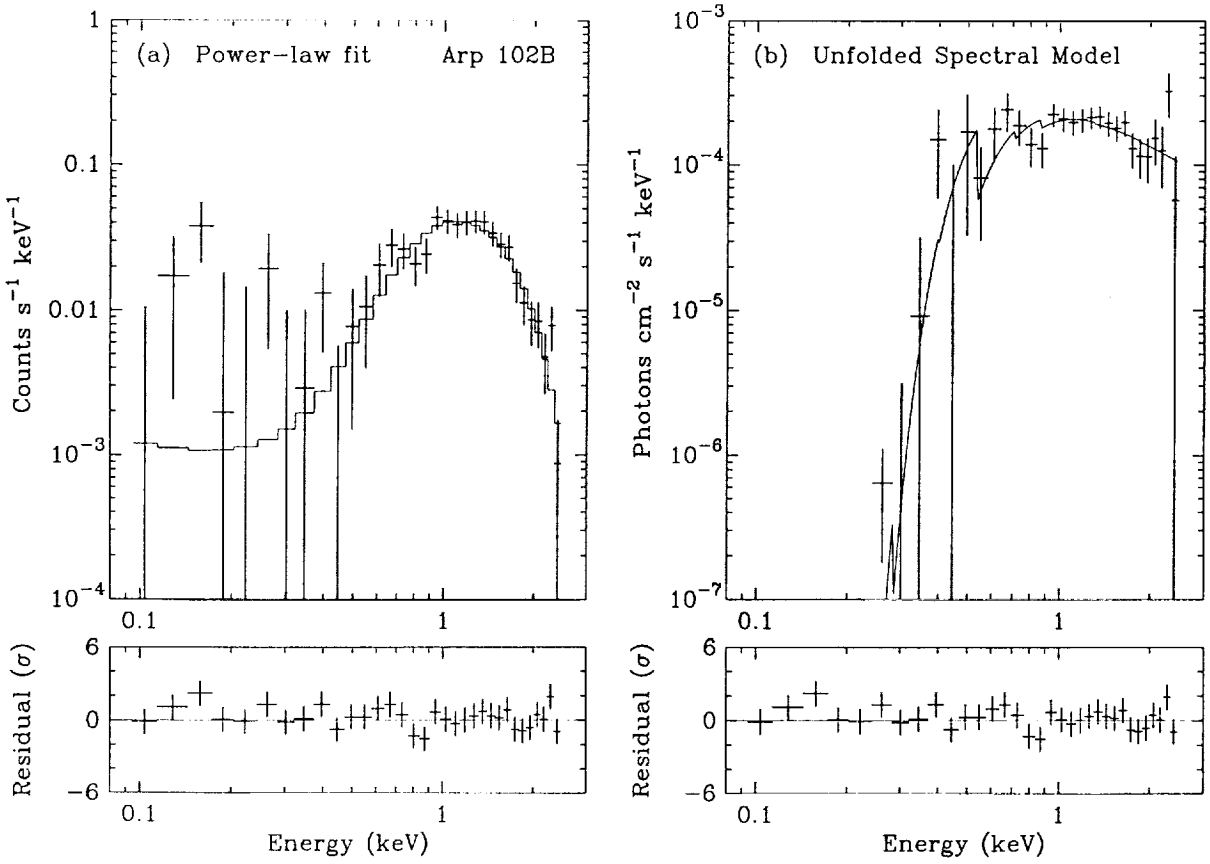
13. Metastable Associated Absorbers in Broad-Line Radio Galaxies

J. P. HALPERN

HST UV spectroscopy of the broad-line radio galaxies Arp 102B and 3C 332 reveal associated absorption lines from low-ionization species including Mg I, Mg II, and Fe II. Most extraordinary is the presence of excited levels of Fe II up to 1.1 eV above the ground state. Aside from these two objects, absorption from metastable levels of Fe II has been seen only in a small (but growing) subset of low-ionization BAL QSOs. I also present a newly released archival *ROSAT* X-ray spectrum of Arp 102B, which is dominated by low-energy absorption. Its X-ray measured column density is considerably larger than that estimated from its UV absorption lines or Balmer emission-line decrements, rendering a "unified absorber" picture problematic for this object.



14. EGRET Sources at Intermediate Galactic Latitude

The identity of the persistent high-energy (> 100 MeV) γ-ray sources in the Galaxy is still largely a mystery. The second installment of the EGRET (2EG) (Thompson et al. 1995) lists a total of 128 sources, of which 51 are likely or possibly identified with AGNs (Montigny et al. 1995), five with rotation-powered pulsars (Thompson et al. 1994), and one is the LMC (Sreekumar et al. 1992). There are 71 unidentified sources, of which 33, or almost half, lie in the narrow band of $|b| \leq 10°$ along the Galactic plane. This excess of low-latitude sources must, therefore, constitute a Galactic population that is either similar to the already identified γ-ray pulsars, or an entirely new class of γ-ray emitters associated with the disk population. We are contining our program, begun in AO6, that is aimed at intermediate-latitude sources, arguing that X-ray detection of them is the most plausible method of identifying the Galactic population. The sources at high latitude must statistically be mostly AGNs, and are more straightforwardly identified through radio and optical means.

The Galactic sources will be difficult to identify. We first describe the observational and theoretical constraints that affect the ability of ROSAT to make an identification of any particular EGRET source. We then describe the choice of targets for which ROSAT is optimally suited, and argue that if they have X-ray properties like any of the already identified sources, then we expect to identify them through followup optical and radio observations of HRI sources detected in their γ-ray error circles. Indeed, X-ray detection may be the *only* means of identifying the majority of EGRET Galactic sources if, as many think, they are pulsars that are radio quiet, or whose narrow radio beams do not cross the earth.

Rotation-powered pulsars seem most likely to explain the Galactic γ-ray source population. The shapes of radio pulsar beams as determined by the highly successful rotating vector model (Radhakrishnan & Cooke 1969) demand that the majority, $\sim 70\%$ of young radio pulsars, are *not* visible from Earth. The clear differences between the broad γ-ray

beam patterns and the narrow radio pulses implies that γ-ray emission is probably visible from a much wider range of directions than are the radio beams. Indeed, the ROSAT identification of the high-energy γ-ray source Geminga as the first radio quiet, but otherwise ordinary pulsar (Halpern & Holt 1992), provides what might be the prototype for the remaining unidentified Galactic sources. Nearly all predictions of the γ-ray pulsar population begin with the understanding that radio detection of most γ-ray pulsars is not a necessary or even an expected occurrence, although a few more radio pulsars may be responsible for EGRET sources that have too few γ-ray photons to reveal their corresponding periods.

Several authors have considered the pulsar hypothesis from statistical or theoretical points of view. Beginning with the properties of the identified EGRET pulsars (Table 1), Halpern & Ruderman (1993) parameterized the observed increase of γ-ray efficiency η with age as $\eta = 0.2\,\tau_5$, where τ_5 is the age in units of 10^5 yr. Using the estimated birth rate of pulsars in the solar neighborhood, they estimated that approximately 23 γ-ray pulsars should be visible to a threshold of 3×10^{-10} ergs cm^{-2} s^{-1}, and that the typical distance would be ~ 1.5 kpc for an assumed scale height of 3°. This total number of 23 would be reduced by any beaming factor that prevents detection through a full 4π steradians. One of the interesting consequences of this scenario is that most pulsars manage to maintain a roughly constant γ-ray luminosity of $\sim 3 \times 10^{34}$ ergs s^{-1} while spinning down, until the efficiency of this process approaches unity. Indeed, Table 1, in which the pulsars are ordered according to decreasing spin-down power $I\Omega\dot{\Omega}$, clearly shows the corresponding increase in γ-ray efficiency.

The most detailed theoretical treatment of the pulsar model for the Galactic γ-ray sources is that of Romani & Yadigaroglu (1995) and Yadigaroglu & Romani (1995). They developed a numerical calculation of γ-ray production and beaming in the outer-gap model that successfully reproduces the basic observed features of the pulse profiles and the γ-ray efficiency as a function of age. By combining this model with a Monte Carlo simulation of the Galactic pulsar population, they estimated that a total of 22 pulsars should be

detected by EGRET at the same flux threshold as was adopted by Halpern & Ruderman (1993), which also approximates the threshold of the first EGRET catalog. This number is remarkably close to the earlier back-of-the-envelope calculation, and to the actual number of EGRET sources. A further result of this simulation is that the mean distance to unidentified γ-ray pulsars should decrease from 3.5 to less than 1 kpc as the age increases from 10^4 to 10^6 yr. Most pulsars are old, of course, and therefore nearby.

If we adopt these pulsar scenarios as the most likely description of the Galactic γ-ray source population, then we should look at the soft X-ray properties of Geminga and the other older pulsars as a guide to planning ROSAT identifications. All of these were detected by ROSAT, with some combination of nonthermal emission, and thermal emission from the surface of the neutron star. The latter is the hallmark of all the older pulsars, with surface temperatures ranging from 5×10^5 K in Geminga (Halpern & Ruderman 1993) and 7×10^5 K in PSR 1055–52 (Ögelman & Finley 1993), to 1.5×10^6 K in Vela (Ögelman, Finley, & Zimmermann 1993). Since most of the γ-ray pulsars are likely to fall in this older age range, we should base our target selection and exposure times on the feasibility of detecting thermal emission, which is the only significant source of X-rays in older pulsars. In fact, there is some evidence that in γ-ray pulsars, the accelerator is responsible for reheating the surface of the neutron star when particles strike the surface (Halpern & Ruderman 1993). PSR 1055–52 is hotter than expected for its age from the standard cooling curves. The X-rays and γ-rays may together sustain the accelerator through pair production. Thus the close association between soft X-ray detected pulsars and high-energy γ-ray sources.

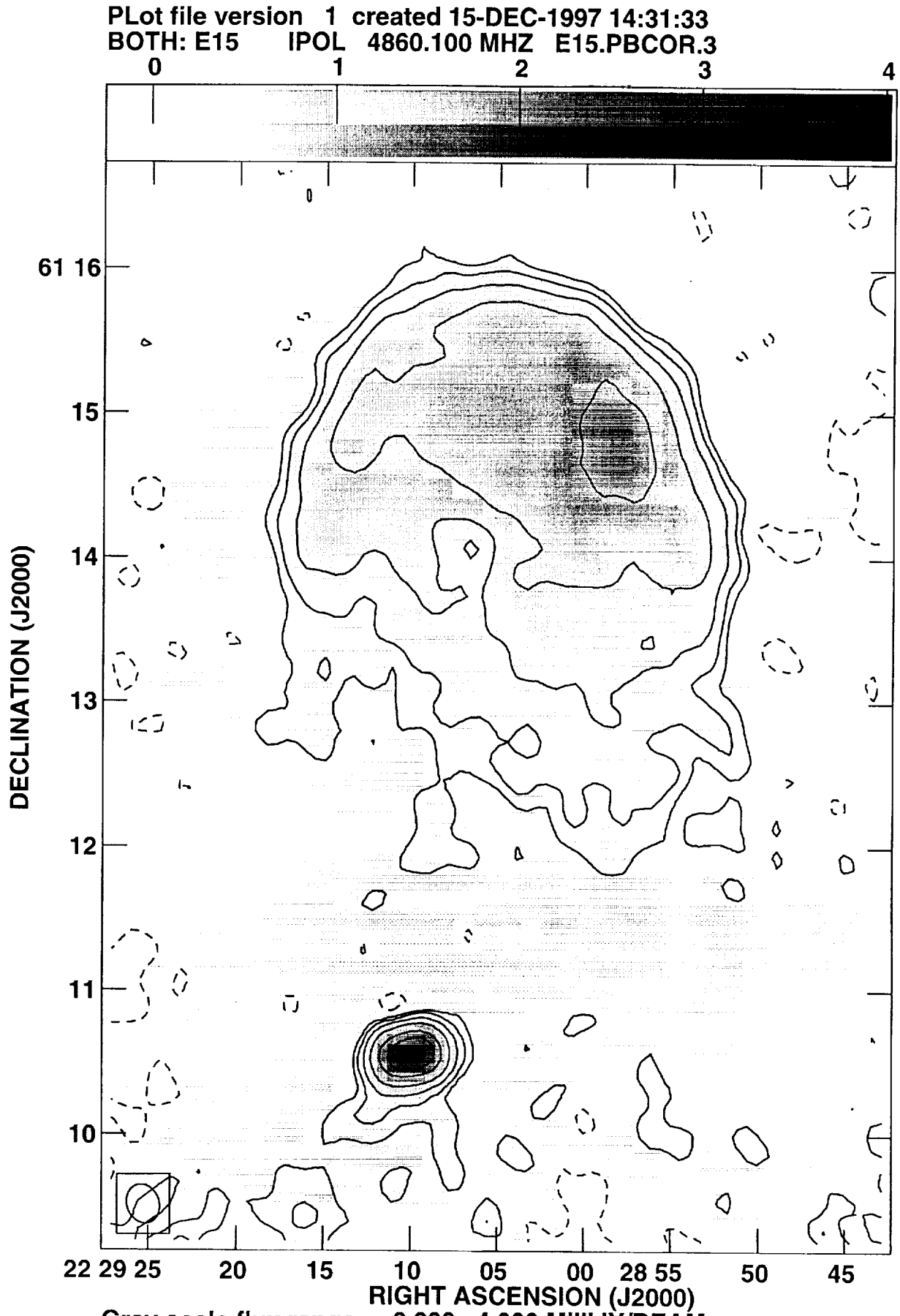
Our basic strategy is to map the error circles of the EGRET sources, looking for sources that may be identified with neutron stars either through their pointlike, thermal emission, or possibly a compact synchrotron nebula in the case of a younger pulsar. Since the HRI does not have the throughput in most cases to detect enough photons to discover a period, the identification of the X-ray source with a neutron star will depend primarily

on followup optical observations to establish the nature (or absence!) of a faint optical counterpart, or possibly a search for a faint radio pulsar counterpart.

For a number of reasons, we can optimize our chances of success by choosing three targets that are found at "intermediate" Galactic latitudes, $3° < |b| < 20°$, and that are not apparently variable. The advantage of this choice is that it increases the likelihood that (*a*) the source is real, (*b*) its position is not affected by errors in the diffuse emission model or nearby weak sources, (*c*) it is nearby, (*d*) the column density is not too high, and (*e*) the corresponding optical fields are not too crowded. The absence of variability is important, since the known γ-ray pulsars show little if any change, while the AGNs are often dramatically variable.

The height above the Galactic plane at which a pulsar will be found is determined by its birth in a young stellar population with scale height ~ 80 pc, and the high velocity which will carry it away from the plane with a mean z-component of 260 km s^{-1} (newly determined by Lyne & Lorimer 1994). Thus, after a time of 10^5 yr, the average pulsar will be found at a height of ~ 100 pc, and after 10^6 yr, at ~ 350 pc. Since both observation and theory say that γ-ray pulsars will be detectable in this age range and at a typical distance of 1–1.5 kpc, the corresponding angular distance from the plane for these typical values is $4° - 20°$, which accounts for our Galactic latitude selection. Older pulsars will have even a larger height and a smaller distance, and Mukherjee et al. (1995) showed that there is statistical evidence for some of them at higher latitudes.

In AO6, we were given 3 targets at Galactic latitudes $3° < |b| < 8°$, and encouraged to continue this program in future AOs. Each of these fields was covered with four overlapping HRI pointings. The HRI has a $38'$ square field. Four pointings whose centers are separated by $27'$, cover a $54'$ diameter that includes the entire 95% error ellipse in each case. For each of these three fields, we also obtained VLA observations on March 31, 1996 to help in the identification of the X-ray sources, and to look for plausible pulsar candidates. We



Grey scale flux range= -0.200 4.000 MilliJY/BEAM
Cont peak flux = 5.2010E-03 JY/BEAM
Levs = 1.0000E-03 * (-0.100, 0.100, 0.200,
0.400, 0.800, 1.600, 2.400, 3.200)

designed the VLA observing program to be sensitive to pulsars by concentrating on low-frequency, 327 MHz mapping. Pulsars are steep-spectrum sources, and could be identified by comparison of our 327 MHz and 1490 MHz maps. The analysis of 327 MHz data is difficult, and has only just begun.

We have carried out optical imaging and spectroscopic observations of approximately 26 HRI sources in these three fields over the past year, using telescopes at Kitt Peak National Observatory and the MDM Observatory. While most are M stars or other bright stars, there are still one or two possibly unidentified sources which therefore remain as γ-ray source candidates.

We were assigned two additional EGRET source fields in AO7, but we have only just begun to receive some of these data. We will soon request VLA observations of the one northern field, 2EG J1635–1427, as we did for our three fields from AO6. The VLA observations are designed to permit the detection of pulsar candidates by looking for steep-spectrum sources, those that are bright at 327 MHz relative to 1490 MHz.

This proposal focuses on the properties of pulsars, because that scenario is the one most dependent upon X-ray searches for identification, and the one with the most stringent requirements on the feasibility. But what if the counterpart is not a pulsar? Although none of these sources has a plausible blazar counterpart (Mattox et al. 1996), it cannot be excluded that an errant blazar will be lurking behind the Galactic plane. ROSAT is ideally suited to discovering a new type of γ-ray AGN, the long-hypothesized "radio-quiet blazar". Other types of Galactic counterparts are much rarer, but easier to identify. The Gregory-Taylor binary LSI +61°303 as a possible counterpart of 2CG 135+01 is a serious example, as is Cygnus X-3 for 2EG J2033+4112. These are bright X-ray sources, well detected by *Einstein* and ROSAT. Optical and radio followups of ROSAT sources will likely be necessary to support the identification process.

APPENDIX

Papers Published Under NASA Grant NAG 5-1935

During the Period 15 March 1992 – 31 October 1997

1. "The True Nature of *IRAS*-Selected, X-ray-Luminous "Normal" Galaxies in the *ROSAT* All Sky Survey," E. C. Moran, J. P. Halpern, & D. J. Helfand, *Ap. J. (Letters)*, **433**, L65 (1994).
2. "No X-ray–Luminous Starbursts in the *Einstein* Medium Sensitivity Survey, Either," J. P. Halpern, D. J. Helfand, & E. C. Moran, *Ap. J.*, **453**, 611 (1995).
3. "A Possible X-ray Detection of the Binary Millisecond Pulsar J1012+5307," J. P. Halpern, *Ap. J. (Letters)*, **459**, L9 (1996).
4. "X-ray Spectra of Cataclysmic Variables from ROSAT," H. R. Richman, *Ap. J.*, **462**, 404 (1996).
5. "Soft X-ray Properties of the Binary Millisecond Pulsar J0437–4715," J. P. Halpern, C. Martin, & H. L. Marshall, *Ap. J.*, **462**, 908 (1996).
6. "A Long *EUVE* Observation of the Seyfert Galaxy RX J0437.4-4711," J. P. Halpern & H. L. Marshall, *Ap. J.*, **464**, 760 (1996).
7. "*ROSAT* PSPC and HRI Observations of the Composite Starburst/Seyfert 2 Galaxy NGC 1672," W. N. Brandt, J. P. Halpern, & K. Iwasawa, *M.N.R.A.S.*, **281**, 687 (1996).
8. "Classification of *IRAS*-Selected X-ray Galaxies in the *ROSAT* All-Sky Survey," E. C. Moran, J. P. Halpern, & D. J. Helfand, *Ap. J. Suppl.*, **106**, 341 (1996).
9. "Extreme X-ray Variability in the Narrow-Line QSO PHL 1092," K. Forster & J. P. Halpern, *Ap. J.*, **468**, 565 (1996).
10. "The Geminga Pulsar: Soft X-ray Variability and an *EUVE* Observation," J. P. Halpern, C. Martin, & H. L. Marshall, *Ap. J. (Letters)*, **473**, L37 (1996).

11. "A Broad-Band X-ray Study of the Geminga Pulsar," J. P. Halpern & F. Y.-H. Wang, *Ap. J.*, **477**, 905 (1997).

12. "E 0336–248: A New BL Lac Object Found by an Old *Einstein*," J. P. Halpern, M. Eracleous, & K. Forster, *Astron. J.*, **114**, 1736 (1997).

13. "Metastable Associated Absorbers in Broad-Line Radio Galaxies," J. P. Halpern, in Proceedings of the Workshop "Mass Ejection from AGNs," Pasadena, CA (1997).

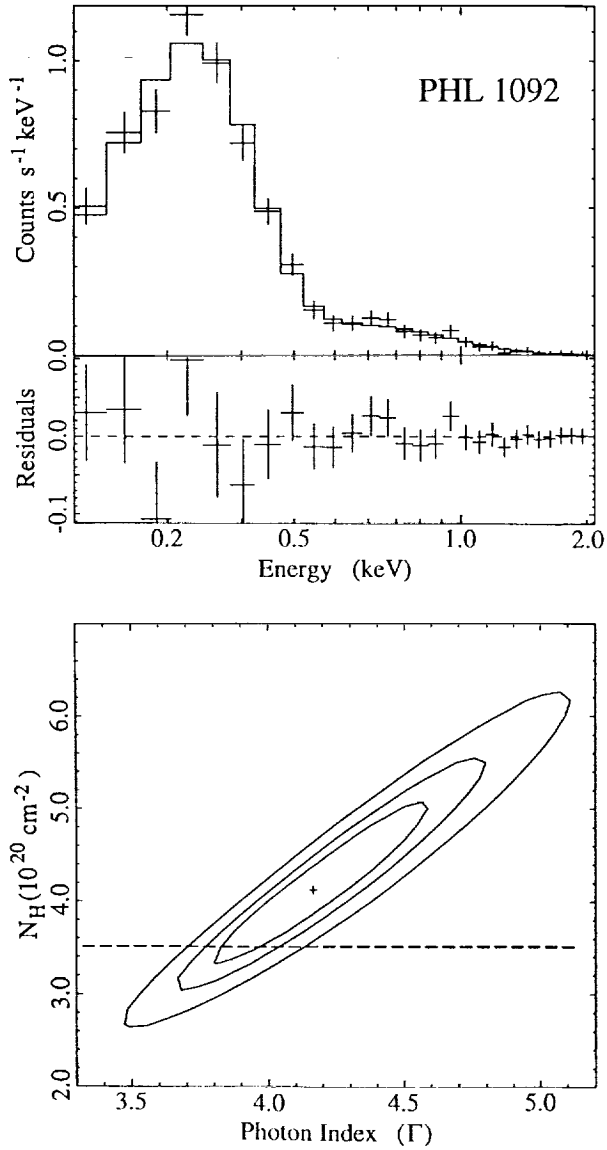


FIG. 1.—*ROSAT* PSPC spectrum of PHL 1092 with best-fitting power-law model. Also plotted are the residuals from the fit and χ^2 contours for the 68%, 90% and 99% confidence limits for the fitted parameters. The horizontal dashed line represents the Galactic N_H on this line of sight from the 21 cm measurement of Murphy et al. (1996).