National Aeronautics and Space Administration

ROSAT

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1. SURFACE EMISSION OF THE GEMINGA PULSAR

1.1. Summary

The Geminga pulsar was observed by the ROSAT PSPC for 37,000 s in September 1993, in order to make a more detailed study than was possible previously of the pulse profile and two-component spectrum, and to do phase-resolved spectroscopy. This exposure was 2.5 times longer than the original discovery observation. In addition, a shorter 4,000 s exposure was made in October 1992, simultaneously with a GRO observation of Geminga, in order to verify the absolute phasing of the X-ray and γ-ray peaks.

We verified that the spectrum can be described as the sum of two black bodies, whose temperatures are $6 \times 10^5$ K and $3 - 4 \times 10^6$ K, with the latter covering $3 \times 10^{-5}$ the area of the former. The pulse profiles indicate that the intensity of the two emitting regions peak $\sim 90^\circ$ out of phase in rotation, but that the temperatures are otherwise independent of phase. An improved estimate of the distance can be made from the cooler (larger) blackbody component, yielding $d = 440 \pm 120$ pc.

1.2. Pulse Profiles and Timing

The pulse profiles of the three PSPC observations of Geminga are shown in Figures 1, 2, and 3. In each Figure, the top panel represents the full energy band over which photons are detected, and the lower three panels are the same data broken into three different energy bands. The October 1992 and September 1993 profiles are basically consistent with the original (March 1991) data as published by Halpern & Holt (1992) and Halpern & Ruderman (1993). The latest observation affords the most detailed look are the light curve. The soft bands, 0.08–0.28 keV and 0.28–0.53 keV, have roughly the same pulse profiles and pulsed fractions, while the 0.5–1.5 keV data are dramatically different. Above 0.5 keV, the phase of the peak changes by about $90^\circ$, and the pulsed fraction approaches 100%. These results are consistent with our original interpretation, namely, that the inclination angle
of the magnetic dipole is large, and that the two hot polar caps are close together on the surface of the star so that they present only one pulse peak per rotation. However, there is still no explanation for the shape and phase offset of the lower-energy data, which must be coming from a large fraction of the surface of the neutron star. A preliminary attempt at pulse phase spectroscopy using this latest observation is described in the next section.

All three PSPC observations of Geminga were corrected to the Solar System barycenter using the latest version of the timing routines in PROS (2.3.1). Using the most recent and accurate EGRET ephemeris (Mattox 1994), we have verified that the three ROSAT light curves maintain the same pulse-phase relationship over the 2.5 year interval between March 1991 and September 1993. However, there seems to be an offset of 1 second in the 1993 timing because the leap second of July 1, 1993 was not added in the PROS barycentering code. We must add this 1 second in order for the latest observation to phase correctly with the previous two, and we assume that this is the correct solution of the problem. The absolute phase with respect to the γ-ray pulse is still uncertain because the ROSAT times are expressed in UTC, rather the TDB (Barycentric Dynamical Time) in which pulsar ephemerides are usually expressed. We are currently checking (with the help of Frank Primini) the reliability of the PROS barycentering code, the accuracy of the ROSAT spacecraft clock, and will convert the photon times to TDB if it seems that this can be done reliably.

1.3. PSPC Spectra

The PSPC spectra can only be fit by a two-component model. We have considered two types of models. One consists of a pair of blackbodies, and the other consists of a black body plus a power-law. These models fit equally well to within the expected errors, and much tighter limits on the parameters are obtained with the most recent long exposure than were possible with the original, published data. The best fits are shown in Figures 4 and 5. In both cases, we have searched the the full four-dimensional Chi-square grids
(e.g., $T_1, T_2 N_H, A_2/A_1$) to derive errors on the spectral parameters. Figure 6 shows the confidence limits for the soft blackbody temperature $T_1$ and $N_H$. Figure 6a is the result for the double blackbody model, and Figure 6b is for the blackbody plus power-law. The temperature is either $6.1 \pm 0.5 \times 10^5$ K, or $5.6 \pm 0.8 \times 10^5$ K, depending on which model is chosen. In both cases, the derived column density is close to $1.0 \times 10^{20}$ cm$^{-2}$, which is consistent with the measurements of $N_H$ in this direction to stars at distances of several hundred parsecs.

An independent estimate of the distance can be derived by assuming that the soft blackbody component comes from the full surface of a neutron star of radius 10 km and making use of the normalization constants in the spectral fits. The resulting contours of equal distance are shown in Figure 6. In the case of the double blackbody fit, a distance of $440 \pm 120$ pc is indicated. This is slightly larger than, but consistent with our published estimate of $250 \pm 150$ pc based on the original data. For the blackbody plus power-law fit, a slightly smaller distance of $350 \pm 150$ pc is found. Either of these results are consistent with the proper motion of Geminga as compared to typical velocities of pulsars (Lyne & Lorimer 1994), and support the model in which Geminga is a highly efficient $\gamma$-pulsar emitting by the outer gap mechanism. In fact, Yadigaroglu & Romani (1995) have independently come up with an independent, theoretical estimate of 400 pc based on such a model.

Figure 7 shows the confidence contours for the properties of the harder blackbody component. The temperature is $3.8 \pm 0.7 \times 10^6$ K, and the fractional area occupied by this component is only $\sim 3 \times 10^{-4}$ of the surface. This is $\sim 10$ times smaller than would be expected for the open-field line polar cap region, which indicates that the heating mechanism is probably not effective along the full open field-line bundle. Alternatively, the harder component may be represented by a power-law. Fits to this model indicate that the power-law energy index is $1.0 \pm 0.4$. 

- 3 -
1.4. Phase-Resolved Spectroscopy

We have made a preliminary attempt at calculating spectra for particular rotation phases. A detailed application of this analysis is still in progress. The folded data were first divided into five phase bins, as shown in Figure 8 (the total data set for the September 1993 observation). Then the five individual pulse height spectra were normalized by their effective exposure times, and divided by the average spectrum. The resulting "ratio" spectra are displayed in Figure 9. Any change in the soft blackbody temperature with rotation phase would make itself evident as a change in slope of the points between 0.1 and 0.5 keV. It can be seen that the temperature is roughly constant with phase, with perhaps a slight decrease in phase bins 1 and 5 where the intensity is smallest, and a slight increase in the other phase bins. This is consistent with a model in which the modulation of the soft blackbody component is due to small differences in temperature over the surface of the star. This will be tested further with detailed spectral fitting. The statistics are poor on the harder component because it contains few photons, even in the summed spectrum. Nevertheless, the temperature at harder energies appears to be greatest in phase bin 2, which contains the peak of the hard component (since it leads the soft pulse by about 90°. Overall, the spectra and pulse profiles appear consistent with our two-temperature model, in which rotation is responsible for carrying the emission regions in and out of view without greatly changing their apparent temperatures.
2. NARROW-LINE SEYFERTS WITH PERMITTED FE II EMISSION

The purpose of this program is to obtain PSPC spectra of an important class of Seyfert galaxies which have narrow lines and strong permitted Fe II emission. Sometimes called I Zw 1 objects, or narrow-line Seyfert 1s, they are crucial to our understanding of Seyfert classification and models of Seyfert unification. Previous to the ROSAT observations, only three of these objects (I Zw 1, Mkn 957, and Mkn 507) had Einstein X-ray data (Halpern & Oke 1987). We observed four new objects, and in addition obtained data on 17 more from the ROSAT archive. The basic properties of these objects are listed in Table 1, and a log of their ROSAT observations is given in Table 2. The results of our spectral fits to simple power-law models, which provide adequate fits in most cases, are described in Table 3. A selection of XSPEC spectral fits and residuals are shown in Figures 11–23.

Most notably, we have found that even though they have narrow emission lines like Seyfert 2 galaxies, the X-ray luminosities of I Zw 1 objects are typical of Seyfert 1s. In addition, their spectra are significantly softer than those of either Seyfert 1 or Seyfert 2 galaxies, showing no evidence for absorption or scattering. In fact, they are often rapidly variable in X-rays, which proves that we have a direct and not a hidden view of their nuclei. Figure 10 shows a light curve of Mkn 957 (=5C 3.100), which displays a rapid dip in flux near the end of the observation.

These results are even more paradoxical in view of the fact that I Zw 1 objects usually have a high ratio of far-infrared to bolometric luminosity, which would be interpreted as evidence for a large covering fraction of obscuring material. We have also found a number of new such objects in the ROSAT/IRAS All-Sky Survey (Moran et al., in press). We are investigating possible correlations between X-ray spectral slope and either Balmer-line width or Fe II line equivalent width (Forster et al., in preparation).
3. DIFFUSE EMISSION AND PATHOLOGICAL SEYFERT SPECTRA

This program combines PSPC and HRI observations of selected Seyfert galaxies which have unusual and variable spectra. The purpose is to disentangle diffuse X-ray emission from the nuclear source, in order to properly interpret the soft X-ray spectral shapes in terms of partial covering and/or warm-absorber models. The targets in the program are NGC 3516, NGC 3227, and NGC 7314. So far, we have performed a detailed analysis only on NGC 3516, and we summarize the results here.

NGC 3516 is historically the Seyfert galaxy with the highest degree of soft X-ray variability. In addition to intrinsic variability of at least a factor of 30, the apparent column density has ranged from $> 10^{24}$ to essentially zero. NGC 3516 also displays variable UV absorption lines of the type that are sometimes thought of as low-velocity analogues of the same phenomenon in BAL QSOs. Figure 24 is our PSPC light curve, which indicates that there was variability of about 25% in one day. The power-law spectral fit displayed in Figure 25 shows the classic signature of deviations due to a warm absorber. Indeed, a fit to a warm-absorber model (Figure 26) is a good fit, with an edge of optical depth 0.9 at 0.75 keV that can be attributed to O VII with a column density of $4 \times 10^{18}$, equivalent to a hydrogen column of $5.7 \times 10^{21}$. Otherwise, there is no significant cold column above the Galactic value of $3 \times 10^{20}$. Dividing the data into high and low states (Figures 27 and 28) reveal no significant differences in the parameters of the absorption edge, as the overlapping confidence contours in Figures 29 and 30 demonstrate. Given that the intensity changed by only 25%, it is not surprising that the properties of the warm absorber remained roughly the same.

We plan to combine these data with historical X-ray spectra and ASCA spectrum that we have also obtained, in order to specify the state of the warm absorber, and relate it to the UV absorption lines and large-amplitude historical X-ray variability.
4. NGC 1672: THE SECOND BRIGHTEST SEYFERT GALAXY

This object is a nearby, southern Seyfert 2 galaxy, and one of the original “composite” Seyfert/starburst galaxies which have evidence for both Seyfert activity and H II regions in their optical spectra. It is one of the lowest luminosity Seyfert 2 galaxies that can be studied in detail. We have obtained both PSPC and HRI observations in order to disentangle the emission from nuclear and starburst activity, both spectrally and spatially. The analysis is still in its early stages, but we do see both nuclear and off-nuclear sources. Figure 31 shows the HRI image in which the nuclear source is the strongest, although it is possibly extended. In addition, there are discrete sources straddling the nucleus in the east-west direction that are probably associated with the star-forming bar that is also oriented in this direction. All of these sources are detected in the PSPC as well, and we plan to do a spatial and spectral analysis of their separate properties.
Table 1. Narrow Line Seyfert Galaxy Sample

<table>
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<th>Name</th>
<th>Other Name</th>
<th>J2000 Coordinates</th>
<th>z*</th>
<th>Class</th>
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<td>00 06 19.5 20 12 10.4</td>
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Redshifts have been obtained recession velocities using the expression:

\[ 1 + z = \left[\frac{(c + V)}{(c - V)}\right]^{0.5} \]

1 Redshifts adapted from observations of USS X-ray Survey AGN, Puchnarewicz et al 1992.
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\(^a\)Total accepted time in seconds.

\(^b\)Count Rate, background subtracted, in counts s\(^{-1}\) through PI channels 3-34 (see §2).
Table 3. Best Fit Spectral Parameters for Powerlaw Models and Estimated Luminosities

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<tr>
<th>Name</th>
<th>$\Gamma$</th>
<th>$N_H$ (10$^{20}$ cm$^{-2}$)</th>
<th>$N_{H}$(Stark)$^a$ (10$^{20}$ cm$^{-2}$)</th>
<th>$A^b$ (10$^{-3}$ cm$^{-2}$ s$^{-1}$ keV$^{-1}$)</th>
<th>$\chi^2_{min}$</th>
<th>$F_{0.1-2.5keV}$ (10$^{-12}$ erg cm$^{-2}$ s$^{-1}$)</th>
<th>$L_{0.1-2.5keV}$ (10$^{43}$ erg s$^{-1}$)</th>
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<td>4.05$^{+0.19}_{-0.19}$</td>
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<td>2.812</td>
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<td>0.56$^{+0.03}_{-0.03}$</td>
<td>0.255</td>
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<td>3.212$^{+0.256}_{-0.234}$</td>
<td>*2.66$^{+0.59}_{-0.50}$</td>
<td>1.81</td>
<td>1.38$^{+0.07}_{-0.07}$</td>
<td>0.404</td>
<td>7.06</td>
<td>7.27</td>
</tr>
<tr>
<td>IRAS 13224-3809</td>
<td>4.297$^{+0.218}_{-0.212}$</td>
<td>**8.44$^{+0.66}_{-0.66}$</td>
<td>5.77</td>
<td>0.90$^{+0.03}_{-0.03}$</td>
<td>1.635</td>
<td>3.97</td>
<td>8.04</td>
</tr>
<tr>
<td>PG 1404+226$^1$</td>
<td>3.353$^{+0.396}_{-0.337}$</td>
<td>2.84$^{+0.96}_{-0.76}$</td>
<td>2.07</td>
<td>0.38$^{+0.04}_{-0.04}$</td>
<td>1.169</td>
<td>2.07</td>
<td>9.29</td>
</tr>
<tr>
<td>Mkn 478</td>
<td>3.447$^{+0.286}_{-0.250}$</td>
<td>*1.57$^{+0.41}_{-0.34}$</td>
<td>1.01</td>
<td>1.79$^{+0.16}_{-0.16}$</td>
<td>0.391</td>
<td>14.68</td>
<td>42.28</td>
</tr>
<tr>
<td>Mkn 486</td>
<td>2.350$^{+4.510}_{-4.170}$</td>
<td>1.46$^{+9.98}_{-1.54}$</td>
<td>1.37</td>
<td>0.14$^{+0.11}_{-0.11}$</td>
<td>0.175</td>
<td>0.54</td>
<td>0.36</td>
</tr>
<tr>
<td>PG 1543+489</td>
<td>3.643$^{+1.330}_{-0.817}$</td>
<td>3.02$^{+2.63}_{-1.54}$</td>
<td>1.60</td>
<td>0.12$^{+0.05}_{-0.05}$</td>
<td>0.362</td>
<td>0.75</td>
<td>71.88</td>
</tr>
<tr>
<td>Mkn 291</td>
<td>2.594$^{+4.609}_{-4.170}$</td>
<td>2.90$^{+11.5}_{-1.54}$</td>
<td>3.46</td>
<td>0.24$^{+0.14}_{-0.14}$</td>
<td>0.221</td>
<td>0.86</td>
<td>0.47</td>
</tr>
<tr>
<td>Mkn 493</td>
<td>2.813$^{+0.383}_{-0.338}$</td>
<td>2.73$^{+0.93}_{-0.75}$</td>
<td>2.02</td>
<td>0.73$^{+0.05}_{-0.05}$</td>
<td>0.348</td>
<td>2.94</td>
<td>1.33</td>
</tr>
<tr>
<td>IRAS 16319+4725</td>
<td>2.488$^{+0.666}_{-0.485}$</td>
<td>0.63$^{+0.86}_{-0.56}$</td>
<td>1.61</td>
<td>0.26$^{+0.08}_{-0.08}$</td>
<td>0.346</td>
<td>1.34</td>
<td>8.56</td>
</tr>
<tr>
<td>IRAS 17020+4544</td>
<td>2.385$^{+0.364}_{-0.339}$</td>
<td>3.35$^{+1.01}_{-0.88}$</td>
<td>2.25</td>
<td>2.60$^{+0.11}_{-0.11}$</td>
<td>0.421</td>
<td>8.26</td>
<td>13.41</td>
</tr>
<tr>
<td>1747.3+6836</td>
<td>2.587$^{+0.177}_{-0.172}$</td>
<td>3.86$^{+0.52}_{-0.48}$</td>
<td>4.31</td>
<td>0.95$^{+0.02}_{-0.02}$</td>
<td>0.884</td>
<td>3.04</td>
<td>5.39</td>
</tr>
<tr>
<td>Mkn 507</td>
<td>1.475$^{+0.732}_{-0.678}$</td>
<td>3.22$^{+3.38}_{-2.16}$</td>
<td>4.42</td>
<td>0.15$^{+0.02}_{-0.02}$</td>
<td>0.436</td>
<td>0.44</td>
<td>0.59</td>
</tr>
<tr>
<td>Mkn 896</td>
<td>2.567$^{+0.258}_{-0.246}$</td>
<td>3.35$^{+0.74}_{-0.65}$</td>
<td>4.74</td>
<td>1.33$^{+0.04}_{-0.04}$</td>
<td>0.537</td>
<td>4.46</td>
<td>1.37</td>
</tr>
</tbody>
</table>
Fig. 1

March 1991

0.07–1.50 keV

0.07–0.28 keV

0.28–0.53 keV

0.53–1.50 keV

Counts

Phase
Figure 2 shows the count rates for different energy bands over a phase range from 0 to 2. The energy bands are 0.08–0.28 keV, 0.28–0.53 keV, and 0.53–1.50 keV. The data covers the period of October 1992.
Fig. 3

September 1993

0.08–1.50 keV

0.08–0.28 keV

0.28–0.53 keV

0.53–1.50 keV

Phase

Counts
Fig. 6
Geminga Phase-Resolved Spectra

Fig. 9
Fig. 10
I Zw 1  
Powerlaw + Absorption

\[ \Gamma = 3.045 \pm 0.137 \quad A = -2.46 \]

\[ N_H (\text{Eis}) = 6.89 \times 10^{20} \text{ cm}^{-2} \]

\[ \chi^2 = 10.44 \quad \chi^2_{\text{red}} = 0.360 \]

\[ f_X = 9.82 \times 10^{-12} \text{ ergs cm}^{-2} \text{ s}^{-1} \]

\[ L_X = 1.61 \times 10^{44} \text{ ergs s}^{-1} \]
PHL 1092  Powerlaw + Absorption

$\Gamma = 4.164 \pm 0.265$  $A_{\tau} = -3.60$

$N_H(\text{Stark}) = 4.13 (3.93) \times 10^{20} \text{ cm}^{-2}$

$\chi^2 = 13.70$  $\chi^2_{\text{red}} = 0.472$

$f_X = 1.95 \times 10^{-12} \text{ ergs cm}^{-2} \text{ s}^{-1}$

$L_X = 1.86 \times 10^{45} \text{ ergs s}^{-1}$
Mkn 1044  Powerlaw + Absorption

$\Gamma = 2.966 \pm 0.935$  $A_T = -2.27$

$N_H^{\text{(Stark)}} = 3.94 (3.04) \times 10^{20} \text{ cm}^{-2}$

$\chi^2 = 24.57$  $\chi^2_{\text{red}} = 0.847$

$f_X = 1.99 \times 10^{-11} \text{ ergs cm}^{-2} \text{ s}^{-1}$

$L_X = 2.39 \times 10^{43} \text{ ergs s}^{-1}$
Fig. 15

Mkn 1239 Powerlaw + Absorption

$\Gamma = 3.885 \pm 0.475$ $A_r = -3.64$
$N_H$ (Stark) = 8.10 $(3.98) \times 10^{20}$ cm$^{-2}$
$\chi^2 = 6.54$ $\chi^2_{red} = 0.225$
$f_X = 8.33 \times 10^{-13}$ ergs cm$^{-2}$ s$^{-1}$
$L_X = 1.40 \times 10^{42}$ ergs s$^{-1}$
Mkn 42  Powerlaw + Absorption

$\Gamma = 2.634 \pm 0.291$, $N_H^{\text{(Stark)}} = 2.44 \times 10^{20}$ cm$^{-2}$

$\chi^2 = 7.52$, $\chi^2_{\text{red}} = 0.259$

$f_x = 1.94 \times 10^{-12}$ ergs cm$^{-2}$ s$^{-1}$

$L_x = 4.99 \times 10^{42}$ ergs s$^{-1}$

Fig. 16
IRAS 13224-3809  Powerlaw + Absorption

\( \Gamma = 4.297 \pm 0.105 \quad A_T = -3.04 \)
\( N_H \text{ (Stark)} = 8.44 \ (5.77) \times 10^{20} \text{ cm}^{-2} \)
\( \chi^2 = 47.43 \quad \chi^2_{\text{red}} = 1.635 \)
\( f_X = 3.97 \times 10^{-12} \text{ ergs cm}^{-2} \text{ s}^{-1} \)
\( L_X = 8.04 \times 10^{43} \text{ ergs s}^{-1} \)

Fig. 17
Mkn 478     Powerlaw + Absorption

$\Gamma = 3.447 \pm 0.122$ \quad $A_T = -2.74$

$N_H \text{ (Stark)} = 1.57 \times 10^{20} \text{ cm}^{-2}$

$\chi^2 = 11.33$ \quad $\chi^2_{\text{red}} = 0.391$

$f_X = 1.47 \times 10^{-11} \text{ ergs cm}^{-2} \text{ s}^{-1}$

$L_X = 4.23 \times 10^{44} \text{ ergs s}^{-1}$
Mkn 493  Powerlaw + Absorption

\[ \Gamma = 2.813 \pm 0.172 \quad \text{and} \quad \alpha = -3.13 \]

\[ N_H (\text{Stark}) = 2.73 \times 10^{20} \text{ cm}^{-2} \]

\[ \chi^2 = 10.08 \quad \text{and} \quad \chi^2_{\text{red}} = 0.348 \]

\[ f_X = 2.94 \times 10^{-12} \text{ ergs cm}^{-2} \text{ s}^{-1} \]

\[ L_X = 1.33 \times 10^{43} \text{ ergs s}^{-1} \]
IRAS 16319+4725  Powerlaw + Absorption

\[ \Gamma = 2.488 \pm 0.249 \quad A_T = -3.59 \]
\[ N_H \text{ (Stark)} = 0.63 \times 10^{20} \text{ cm}^{-2} \]
\[ \chi^2 = 10.03 \quad \chi^2_{\text{red}} = 0.346 \]
\[ f_X = 1.34 \times 10^{-12} \text{ ergs cm}^{-2} \text{s}^{-1} \]
\[ L_X = 8.56 \times 10^{43} \text{ ergs s}^{-1} \]
IRAS 17020+4544  Powerlaw + Absorption

\[
\begin{align*}
\Gamma &= 2.385 \pm 0.166 \quad A_r = -2.58 \\
N_H (\text{Stark}) &= 3.95 \times (2.25) \times 10^{20} \text{ cm}^{-2} \\
\chi^2 &= 12.20 \quad \chi^2_{\text{red}} = 0.421 \\
f_X &= 8.26 \times 10^{-12} \text{ ergs cm}^{-2} \text{ s}^{-1} \\
L_X &= 1.34 \times 10^{44} \text{ ergs s}^{-1}
\end{align*}
\]
Mkn 507  Powerlaw + Absorption

\[ \Gamma = 1.475 \pm 0.325 \quad A_r = -3.83 \]
\[ N_H^{\text{(Stark)}} = 3.22 \times 10^{20} \text{ cm}^{-2} \]
\[ \chi^2 = 12.63 \quad \chi^2_{\text{red}} = 0.436 \]
\[ f_X = 4.37 \times 10^{-13} \text{ ergs cm}^{-2} \text{ s}^{-1} \]
\[ L_X = 5.89 \times 10^{42} \text{ ergs s}^{-1} \]
Mkn 896  Powerlaw + Absorption

\[ \Gamma = 2.567 \pm 0.120 \quad A_T = -2.88 \]

\[ N_H \text{ (Stark)} = 3.35 \times (4.74) \times 10^{20} \text{ cm}^{-2} \]

\[ \chi^2 = 15.56 \quad \chi^2_{\text{red}} = 0.537 \]

\[ f_X = 4.46 \times 10^{-12} \text{ ergs cm}^{-2} \text{ s}^{-1} \]

\[ L_X = 1.37 \times 10^{43} \text{ ergs s}^{-1} \]

Fig. 23
NGC 3516  October 1992  Lightcurve  All Counts (0.1 - 2.5 keV)

Fig. 24

Bin (sec) = 120  Time (sec)

Bin (sec) = 120  Time (sec)
NGC 3516  Powerlaw + Absorption

\[ \Gamma = 2.194 \pm 0.022 \quad A_T = 1.82 \]

\[ N_H \text{ (Stark)} = 2.89 \times 10^{20} \text{ cm}^{-2} \]

\[ \chi^2 = 482.8 \quad \chi^2_{\text{red}} = 16.65 \]

\[ f_X = 4.77 \times 10^{-11} \text{ ergs cm}^{-2} \text{ s}^{-1} \]

\[ L_X = 1.55 \times 10^{43} \text{ ergs s}^{-1} \]
NGC 3516  
Powerlaw + Absorption Edge + Galactic Absorption

\[ \Gamma = 2.170 \pm 0.027 \quad A_T = -1.71 \]

\[ N_H (\text{Stark}) = 3.34 \times 10^{20} \text{ cm}^{-2} \]

\[ \chi^2 = 40.77 \quad \chi^2_{\text{red}} = 1.510 \]

Edge Energy = 0.749 keV

\[ \tau_{\text{max}} = 0.919 \]

\[ f_X = 5.28 \times 10^{-11} \text{ ergs cm}^{-2} \text{ s}^{-1} \]

\[ L_X = 1.72 \times 10^{43} \text{ ergs s}^{-1} \]

Fig. 26
NGC 3516 High State  Powerlaw + Absorption Edge + Galactic Absorption

$\Gamma = 2.213 \pm 0.035 \quad A_F = -1.67$

$N_H (\text{Stark}) = 3.45 (2.89) \times 10^{20} \text{ cm}^{-2}$

$\chi^2 = 28.45 \quad \chi^2_{\text{red}} = 1.054$

Edge Energy = 0.736 keV

$\tau_{\max} = 0.945 \quad \chi^2_{\text{CQO}} = 3.45 \times 10^6 \text{ cm}^{-2}$

$\tau_{\max} = 5.86 \times 10^{13} \text{ cm}^{-2}$

$f_X = 5.73 \times 10^{-11} \text{ ergs cm}^{-2} \text{ s}^{-1}$

$L_X = 1.87 \times 10^{43} \text{ ergs s}^{-1}$

Fig. 27
NGC 3516 Low State  Powerlaw + Absorption Edge + Galactic Absorption

$\Gamma = 2.098 \pm 0.048 \quad A_T = -1.71$

$N_H (\text{Stark}) = 3.15 (2.89) \times 10^{20} \text{ cm}^{-2}$

$\chi^2 = 28.46 \quad \chi^2_{\text{red}} = 1.054$

Edge Energy = 0.774 keV

$\tau_{\text{max}} = 0.882 \quad \frac{N_H}{L} = 3.64 \times 10^{-6}$

$f_X = 4.61 \times 10^{-11} \text{ ergs cm}^{-2} \text{ s}^{-1}$

$L_X = 1.50 \times 10^{43} \text{ ergs s}^{-1}$

Fig. 28
NGC 1672

ROSAT HRI QPOE (Level 2 Sky Coordinates)

Fig. 31
APPENDIX

Papers Published Under NASA Grant NAG 5-1935

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 ($m_r = 10.06$) 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 $\alpha_{2000} = 16^h15^m35^s, \delta_{2000} = +36^\circ10^\prime48^\prime$.

MORAN, HALPERN, & HELFAND (see 433, L66)
THE TRUE NATURE OF IRAS-SELECTED, X-RAY-LUMINOUS "NORMAL" GALAXIES IN THE ROSAT ALL-SKY SURVEY

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ABSTRACT

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 IRAS/ROSAT galaxies that includes 20 with extreme X-ray luminosities \( L_X = 10^{42}-44 \text{ ergs s}^{-1} \) 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 reexamined 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 \( L_X \approx 10^{42} \text{ ergs s}^{-1} \) 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 \( 10^{42} \text{ ergs s}^{-1} \), and claims of a new class of X-ray–luminous spiral galaxies are not supported by this study.

Subject headings: galaxies: Seyfert — galaxies: starburst — X-rays: galaxies

1. INTRODUCTION

The cosmic X-ray background (XRB) is thought to originate from the integrated emission of discrete sources. The main weakness of this explanation is, however, that the characteristic spectra of known classes of extragalactic X-ray emitters are all considerably softer than the spectrum of the XRB itself. Since active galactic nuclei (AGNs) are the dominant class of extragalactic X-ray sources at high fluxes, it is commonly believed that they are responsible for the vast majority of the XRB. However, the space density and correlation length scale of AGNs, in addition to their typical broad-band X-ray spectra, are incompatible with an XRB origin in which AGNs contribute more than ~50% of the 2–10 keV flux (Fabian & Barcons 1992, and references therein). Furthermore, the best estimate to date of the soft X-ray luminosity function of AGNs (Boyle et al. 1993) rules out AGNs producing all of the XRB.

The contribution of star-forming galaxies to the XRB has been frequently considered, at both soft and hard X-ray energies (Persic et al. 1989; Griffiths & Padovani 1990; Lonsdale & Harmon 1991; Fruscione & Griffiths 1991; Rephaeli et al. 1991; Green, Anderson, & Ward 1992; David, Jones, & Forman 1992). The most plausible scenario for such a contribution, suggested by Griffiths & Padovani (1990), proposes that galaxies undergoing bursts of star formation in regions of low metallicity could spawn enough luminous high-mass X-ray binaries to have both high-integrated X-ray luminosities (> \( 10^{42} \text{ ergs s}^{-1} \)) and spectra well matched to the spectrum of the XRB. Possible examples of such starburst galaxies have surfaced in a recently published study of infrared- and X-ray-selected galaxies, which has claimed to find a new class of X-ray–luminous, “normal” (non-AGN) galaxies (Boiller et al. 1992). In this Letter we present the results of our investigation of these allegedly normal spiral galaxies with extreme X-ray luminosities.

2. SAMPLE SELECTION AND OBSERVATIONS

The targets for this study were selected from Boller et al. (1992), who cross-correlated the ROSAT All-Sky Survey (RASS) with the IRAS Point Source Catalog (PSC). A total of 244 IRAS galaxies were found to be positionally coincident with ROSAT X-ray sources (within 100'). Optical identifications and classifications for most of these objects were found in the NASA/IPAC Extragalactic Database (NED). For 104 galaxies with published redshifts, the X-ray luminosity \( L_X \) in the 0.1–2.4 keV band was determined. Surprisingly, 20 of the 67 galaxies for which \( L_X \) exceeded \( 10^{42} \text{ ergs s}^{-1} \) were reported as normal spirals or starbursts, despite X-ray luminosities that are characteristic of Seyfert galaxies. These 20 objects, with \( L_X \) ranging from \( ~2 \times 10^{42} \) to \( ~3 \times 10^{44} \text{ ergs s}^{-1} \), are several to several hundred times more luminous than the brightest spirals observed with the Einstein Observatory, and two to four orders of magnitude more luminous than typical spiral galaxies (Fabbiano 1989). Such remarkable high-energy luminosities represent a challenge to our current understanding of the production of X-rays in ordinary spirals. If their classifications are correct, the existence of high-\( L_X \) normal galaxies bears important implications for the problem of the XRB. An important first step toward understanding the true nature of the 20 X-ray–luminous spirals must be reliable spectroscopic classification.

We observed 13 high-\( L_X \) IRAS/ROSAT galaxies, primarily using the KPNO 2.1 m telescope and Goldcam CCD spectrograph, but also with the Shane 3 m telescope and Kast spectrograph at Lick Observatory and with the CTIO 4 m telescope and RC spectrograph. The spectra have sufficient resolution (4–7 Å full width at half-maximum [FWHM]) and wavelength coverage (most extend from ~3700 to 7400 Å) to allow us to...
classify accurately each object. For four additional high-$L_X$ spirals, we found spectra in the literature sufficient for accurate classification, bringing the total number of object classifications reexamined here to 17.

3. SPECTROSCOPIC CLASSIFICATION

The classification of an emission-line galaxy depends on the velocity widths and intensity ratios of the emission lines observed in its optical spectrum. Unfortunately, there is no single prescription for this task; therefore, we adopt the following guidelines. Emission lines broader than $\sim 300$ km s$^{-1}$ FWHM—too broad to result solely from a spiral galaxy rotation curve, and indicative, therefore, of a massive object in the nucleus—earn a galaxy an AGN classification. A galaxy whose emission-line flux ratios indicate that the ionizing continuum is produced by hot stars (Veilleux & Osterbrock 1987; Filippenko & Terlevich 1992) is also classified as an AGN, regardless of its line widths. We require that an object exhibit both narrow emission lines and H $\gamma$ region-like line flux ratios to be classified as an H $\text{II}$ galaxy. Herein we refer to all non-AGN spiral galaxies (starbursts and more quiescent star-forming galaxies) collectively as H $\text{II}$ galaxies, placing emphasis on the common mechanism powering their emission lines—hot stars—rather than their star formation rates.

Table 1 summarizes the available spectroscopic data, our classification and its basis, and the relevant references for each of the high-$L_X$ galaxies. Our new optical spectra are displayed in Figure 1. We find that 13 objects are, in fact, AGNs; the remaining four are indeed H $\text{II}$ galaxies with putative X-ray luminosities in excess of $10^{42}$ ergs s$^{-1}$. However, as we discuss below, the identification of three of these H $\text{II}$ galaxies with ROSAT X-ray sources is doubtful.

4. CHANCE COINCIDENCES

Boller et al. included in their sample all cases for which the IRAS/ROSAT position offset is less than 100" and acknowledged that a fraction of the IR/X-ray coincidences must arise by chance. The distribution of optical/X-ray position offsets (very similar to the distribution of IR/X-ray offsets) provides the best means for determining which entries in the sample are likely to be chance coincidences. RASS sources are located within 20" of their optical counterparts 70% of the time (Brinkmann, Siebert, & Boller 1994); thus, only one genuine identification in the entire Boller et al. sample of 244 should have an optical/X-ray offset $\Delta_{\alpha\beta}$ as large as 60", assuming the true distribution of $\Delta_{\alpha\beta}$ is Gaussian. Among the 20 high-$L_X$ spirals, five have $\Delta_{\alpha\beta} > 60"$. Either the chance coincidences are concentrated in this subsample, or there are other systematics affecting the Boller et al. RASS X-ray source positions. Table 1 lists the values of $\Delta_{\alpha\beta}$ for each high-$L_X$ galaxy.

IRAS 16137+3618, which we observed to be an H $\text{II}$ galaxy (Fig. 1), is a clear example of a chance coincidence. Figure 2 (Plate L2) displays the optical finding chart with the IRAS error ellipse and the RASS source position marked. Assuming this to be a real IR/X-ray match, Boller et al. reported that $L_X = 3 \times 10^{44}$ ergs s$^{-1}$ for this H $\text{II}$ galaxy. Notice, however, that the RASS source position falls directly on a bright star ($m_v = 10.06$) 85" away from the galaxy. The star is virtually certain to be the X-ray source. Two of the AGNs, UGC 3478 and Mrk 520, and one H $\text{II}$ galaxy, UGC 838, have $\Delta_{\alpha\beta} = 79", 60 "$, and 66", respectively. If these are also chance coincidences, the total number is consistent with the Boller et al. estimate that the chance coincidence rate for the high-$L_X$ spirals should be 20%. For the final large $\Delta_{\alpha\beta}$ object, IRAS 16155+6831 (an H $\text{II}$ galaxy), we have learned (T. Boller 1994, private communication) that the X-ray source has been deleted from the X-ray catalog following a more recent processing of the RASS data.

5. DISCUSSION

To summarize our census of 17 of the 20 high-$L_X$ "normal" spiral galaxies in the Boller et al. sample of X-ray-selected IRAS galaxies, we find that 13 are actually AGNs. Four others are H $\text{II}$ galaxies. However, two of these H $\text{II}$ galaxies are incor-
Fig. 1.—New spectra of 10 of the high-$L_\text{X}$ galaxies. All but two [(a) and (j)] are AGNs. The vertical scales, in units of ergs cm$^{-2}$ s$^{-1}$ Hz$^{-1}$, have been normalized to unity. Not shown are our spectra of IRAS 16155+6831 (not an RASS source), Mrk 520 (Sey 1.9 spectrum published by Lonsdale et al. 1992), and Kaz 49 (Sey 1.9 spectrum published by Yegiazarian & Khachikian 1988).
correctly identified as X-ray sources, and the X-ray source originally associated with a third is not found in the current version of the RASS. Two of the AGNs may be also incorrectly identified as X-ray sources given their large $\Delta_{\nu X}$ values. Thus, misclassifications, chance coincidences, and other errors are largely responsible for creating the illusion that a high fraction of the objects in the Boller et al. sample are normal galaxies with extreme X-ray luminosities.

Objects in the literature, and therefore in NED, have been classified for a variety of purposes using methods which differ in quality and accuracy. Thus, NED cannot be relied upon as the sole resource for establishing new classes of objects such as the high-$L_x$ spirals. Perusal of the spectra in Figure 1 immediately reveals that several objects have Seyfert properties that are quite subtle. It is no surprise that these were previously misclassified as normal galaxies. The most dramatic case is that of NGC 3147. Kennicutt (1992) included this galaxy in his atlas as an example of a typical Sb spiral. Indeed, the emission lines in the integrated light spectrum are narrow with H II region-like ratios, since most of the emission line flux arises in extranuclear H II regions. The nuclear spectrum, however, indicates a strongly inverted [N II]/H$\alpha$ ratio (only partially affected by a stellar H$\alpha$ absorption feature) and broad [N II] lines (FWHM = 404 km s$^{-1}$). NGC 3147 is almost face-on, so this broad band must arise in an active nucleus, which, although optically weak, is likely to be responsible for most of the X-ray emission from this object.

In the case of NGC 3256, the sole high-$L_x$ H II galaxy for which the identification with a ROSAT X-ray source is secure, $L_x = 2 \times 10^{42}$ ergs s$^{-1}$. This is not substantially greater than highest X-ray luminosities known previously for H II galaxies (several $10^{42}$ ergs s$^{-1}$; Fabbiano, Kim, & Trinchieri 1992). All of the objects with $L_x > 3 \times 10^{42}$ ergs s$^{-1}$ have turned out to be Seyfert galaxies. This result stands even if the H II galaxy UGC 838 is an RASS source, since it would have $L_x = 1.8 \times 10^{42}$ ergs s$^{-1}$. Thus, we conclude that NGC 3256 is probably a resident of the high-luminosity tail of the X-ray luminosity function for normal H II galaxies rather than a representative of a new class of X-ray–luminous spirals. These conclusions are supported by our larger followup study (Moran et al. 1994) of the unclassified members of the Boller et al. sample. All 51 objects observed to date are AGNs, stars, or H II galaxies with $L_x < 10^{42}$ ergs s$^{-1}$.

The sources of X-rays in normal spiral galaxies consist of accreting low- and high-mass X-ray binaries, supernova remnants, diffuse emission from the hot phase of the interstellar medium, and stars (Fabbiano 1989). If the X-ray emission in NGC 3256 arises due to these same sources in a combination similar to that in lower luminosity spirals, luminous H II galaxies such as this will have little impact on the XRB puzzle: their X-ray spectra would be too soft to contribute much flux to the background above $\sim 3$ keV, where the spectra of known classes of X-ray emitters and that of the XRB are most discrepant. Analysis of the broad-band X-ray spectrum of NGC 3256 obtained by ASCA will settle this question (Moran & Helfand 1994). Despite these discouraging prospects, the picture for a significant contribution to the XRB by H II galaxies as painted by Griffiths & Padovani (1990) cannot be ruled out. The soft X-ray selection of the Boller et al. sample might easily miss H II galaxies with large amounts of intrinsic absorption and, therefore, hard emitted spectra. With the exception of a handful of quasars, all the classified Boller et al. objects we know of ($> 150$) have modest redshifts ($z < 0.15$) due to the sensitivity limits of the IRAS PSC and the RASS from which they were drawn; thus, the possibility of a population of star-forming galaxies at moderate redshifts with different spectral properties remains. X-ray images deeper than the RASS will have to be used to probe for X-ray-luminous H II galaxies at earlier epochs.

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REFERENCES