A Lunar Occultation of the Dust-Scattering Halo Around GX 5-1 Observed with ROSAT

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The x-ray source GX 5-1 in the galactic bulge has been observed with the position-sensitive proportional counter onboard the Röntgen satellite (ROSAT) during and after a lunar occultation. Extended emission around the source was unambiguously discovered while the central source was behind the lunar rim. This emission is interpreted as a dust-scattering halo around GX 5-1 that has a fractional intensity of 28 percent, implying a grain column density between GX 5-1 and Earth of ~3 × 10^{10} per square centimeter. The halo derived from imaging during the ROSAT all-sky survey is identical to that obtained from the lunar occultation, thus demonstrating that the ROSAT x-ray mirror scattering has not changed as compared with the mirror properties as measured in preflight calibrations.

In the 1960s, the possible existence of halos, produced by the scattering of x-rays off dust grains in the interstellar medium, around the stronger and moderately absorbed x-ray sources was first discussed (*1*). Such dust-scattering halos offer interesting diagnostic possibilities for the study of the physical properties of interstellar dust grains, in particular, their size distribution and chemical composition as well as their spatial distribution along the line of sight. These properties have remained elusive despite a substantial observational effort to study dust at optical and infrared wavelengths. In contrast to all other wavelengths, the two contributors to the extinction, namely, absorption and scattering, can be observed separately within one measurement at x-ray wavelength.

From the observational point of view, the study of dust halos at x-ray wavelengths has been difficult; one is essentially looking for weak, extended surface brightness around a strong point-like source, a task that is next to impossible without x-ray imaging techniques. However, even with an imaging x-ray telescope, the search for halos remains challenging: x-ray scattering off the mirrors of the x-ray telescope, a purely instrumental effect, leads to an x-ray brightness profile that looks quite similar to the expected astronomical dust-scattering halo. The first dust halo observations have been made with the Einstein Observatory on about a dozen sources (*2, 3*). Early ROSAT results have been reported on GX 339-4 (*4*).

The observations of x-ray halos with imaging telescopes are problematic for two reasons (*5*): First, such observations rely heavily on the preflight telescope calibration, which may well have changed during flight, and second, the mirror scattering is wavelength-dependent, and thus an inadequate knowledge of the intrinsic source spectrum can lead to errors in the estimate of the point response function (PRF) of the telescope.

The only way to avoid subtracting a telescope PRF from the observed surface brightness distribution and to directly measure an extended halo consists in obscuring the strong central point source and thereby "removing" the scattering contribution of the mirror. This can be accomplished by a lunar occultation of the x-ray source.

With the Ginga satellite, extended emission around the transient source GS 1741.2-2859/1741.6-2849 was detected during a lunar occultation observation of the galactic center region (*6*). The instrument used for this observation was a large-area proportional counter (LAC) with a field of view of 2° by 1° (full width at half maximum) without any imaging capability. Therefore, the light curve during occultation ingress and egress had to be modeled in order to obtain the properties of the dust-scattering halo. Because of an excess in the most energetic bin (7 to 9.4 keV) of the spectrum, the investigators concluded that the grains responsible for the scattering are probably composed of iron. This result has been questioned (*7*) because there is not nearly enough cosmic iron to produce the volume of interstellar grains known to be present in space from applying the Kramers-Kronig relations to the observed interstellar extinction law (*8*). Furthermore, one cannot exclude the possibility that in such a nonimaging observation x-ray halos are confused with structures in the diffuse galactic emission.

For a low-orbit satellite such as ROSAT, there are only a few sufficiently bright x-ray sources that can be occulted by the moon, most of which are located in the galactic center region. Although the moon passes through the galactic center region once every month, ROSAT can observe this region only twice per year because the "look" direction must be 90° ± 15° away from the sun direction. The moon moves with a speed of ~0.5° hour^{-1} along its orbit and carries out an apparent parallactic loop-like motion when viewed from ROSAT in its Earth orbit; the ROSAT velocity component dominates the relative motions and leads to typically one or two eclipses of a given x-ray source when viewed from the spacecraft. Further constraints, which must be obeyed by the spacecraft and the instruments onboard, further limit the observability of a lunar occultation event. First, Earth must not block the viewing direction; second, the spacecraft must not be within Earth's radiation belts or the South Atlantic Anomaly; and third, the viewing direction must not come too close to the instantaneous satellite velocity vector (in order to avoid the possible deposition of atomic oxygen onto the x-ray detectors). During the first half year of pointed observations made by ROSAT, there was only one bright source occulted by the moon, GX 5-1. This event was observed with the position-sensitive proportional counter (PSPC) on ROSAT, and in this report we describe the lunar occultation observation of an x-ray source with an imaging x-ray telescope.

The observation of GX 5-1 was performed on 9 March 1991 between 11:06:19 and 11:25:31 UT (universal time). The eclipse egress occurred at 11:17:22 UT with an apparent speed of the moon of 2.32 arc sec s^{-1}; the egress lasted less than 1 s, indicating that the source is actually point-like.

During the observation, the measurement of ROSAT's attitude was degraded. With the moon in the field of view, the guidance control star tracker is disabled by the brightness of the sunlit side. Thus, only the gyroscope information was available. This exhibited a slight offset to the true attitude, which was determined from the known position of GX 5-1 (*9*) to be 1.8 arc min in right ascension (RA) and 7.4 arc min in declination at the time of the egress. For the same reason, the ROSAT attitude drifted with a speed of −0.17 arc sec s^{-1} in RA and +0.13 arc sec s^{-1} in declination. We determined this correction by comparing the position of GX 5-1 every 10 s after the egress with the position as determined from the ROSAT all-sky survey [RA(2000) = 18^{hr} 01^{m} 01^{s}; declination (2000) = −25°05′10″].

After all the attitude corrections had been applied, images were created in celestial as well as lunar coordinates. Figure 1 shows two images in lunar (that is, selenocentric) coordinates. The left image comprises 263 s of observation time ending just before the egress of GX 5-1. For the right image, the observation time has been extended 10 s over egress, just enough to exhibit the source but still without the distortion of

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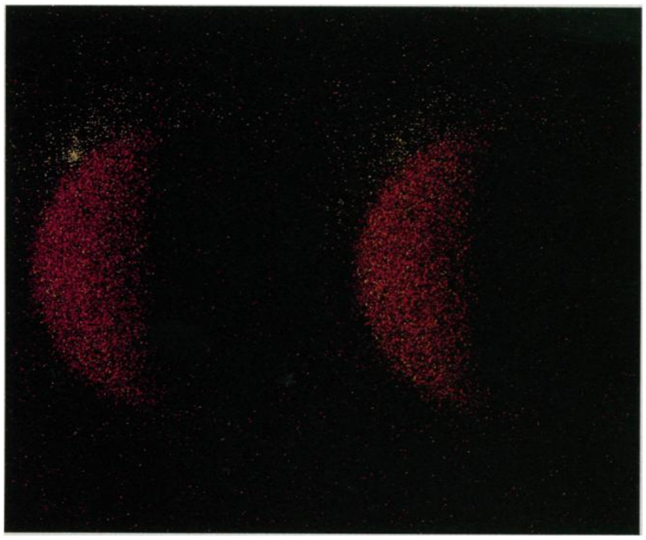

Fig. 1. The moon and GX 5-1 in lunar coordinates. The left image comprises 263 s of observation time just ending before the egress; the right image extends this time 10 s over the egress. The (soft) photons from the moon are represented in red and the (hard) x-rays from GX 5-1 in yellow.

the apparent movement of GX 5-1. In both images, we utilized the PSPC's spectral resolution for color coding. The x-rays coming from the moon's surface are rather soft; they are representative of the solar x-ray spectrum with a mean photon energy (in the ROSAT band pass) between 0.2 and 0.25 keV (*10*). On the other hand, GX 5-1 is among the most strongly absorbed x-ray sources observable with ROSAT ($N_H \sim 3.3 \times 10^{22}$ cm^{-2}) (*11*); the mean photon energy of GX 5-1 in the ROSAT band pass is 1.65 keV. We have color-coded soft photons in red and hard photons in yellow so that essentially all photons of lunar origin appear red while all photons associated with GX 5-1 and its halo appear yellow. The extended emission of hard x-rays can be clearly seen before and after egress. This unambiguously indicates the presence of scattering between GX 5-1 and the moon.

When determining the surface brightness distribution of a halo around an x-ray source eclipsed by the moon, two things are important: (i) If one considers the moon as a shutter, the observation time is not uniform for all parts of the halo. (ii) All photons from the moon (*10*) must be separated from the image because their contribution to the surface brightness is far too large to be ignored; this is especially the case for our observation, where the egress of GX 5-1 occurred on the bright side of the moon.

The separation of the lunar photons by spectrum only is, however, not sufficient because the moon (or rather, the sun) also radiates above 1 keV (of course, with much lower intensity). Therefore, a procedure based on a spatial criterion has been applied: all photons considered to belong to the lunar disk were removed from the analysis. Thereby, a diameter of the moon had to be chosen that was larger by about 12 arc sec from the actual apparent diameter (radius = 14.95 arc min) but consistent with the known angular resolution of the PSPC. During the observation, the apparent diameter of the moon also slightly increased because of ROSAT's orbital motion. However, because this increase was only ~20 arc sec over the entire observation period, we ignored this additional complication. Hence, with the described method we could remove the moon photons and also one (weak) serendipitous x-ray source 40 arc min away from GX 5-1.

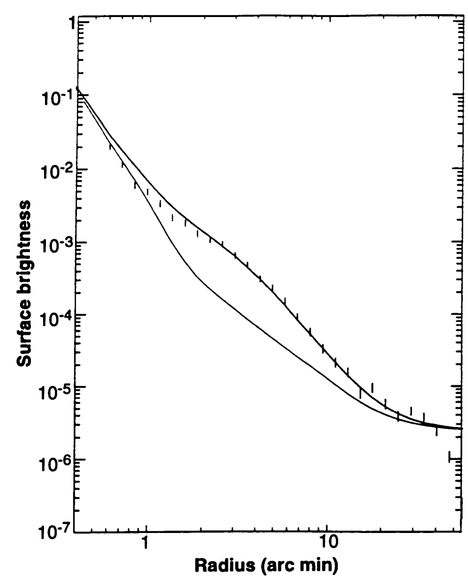

Fig. 2. Normalized surface brightness distribution for GX 5-1 after the eclipse egress. The normalization has been done with respect to the total source intensity after subtraction of the background. Measured data are represented by their 1σ error bars. The model PRF of the ROSAT telescope together with the background is shown as the lower line. The measured plus model surface brightness distribution is indicated by the upper line. The halo surface brightness distribution is based on a dust grain size distribution $n(a) \sim a^{-3.5}$ for grain sizes between 0.0003 and 0.3 μm. From our analysis, a fractional halo intensity of 28.2% is derived.

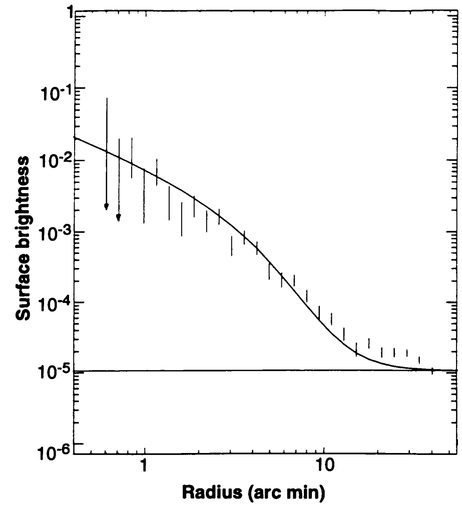

Fig. 3. Normalized surface brightness distribution for GX 5-1 before the eclipse egress. The normalization has been performed in the same manner as in Fig. 2.

The total observation has been split into two intervals: the first extends over 310 s and ends 3 s before egress, the other one starts 2 s after egress and lasts 235 s. The surface brightness distribution was determined in the same general way as described previously (*3, 4*) but modified for this special application: all counts were radially binned around the position of GX 5-1 (determined from the centroid of the observed photon distribution) and subsequently divided by the areas of the rings which, in this case, are reduced by the moon acting as a shutter. Because the moon was moving during the observation, a time-dependent exposure map was calculated and binned in the same manner as the surface brightness distribution. An additional complication arose from the fact that the x-ray telescope's sensitivity is not uniform over the field of view ("vignetting"); this effect was included in the calculation of the exposure map.

The whole procedure was applied separately for the two periods before and after the egress. Figures 2 and 3 show the measured surface brightness distributions for the two periods. After subtraction of the background (5.6×10^{-5} count s^{-1} arc min^{-2}), the halo intensity was 6.1 count s^{-1} for the period before the egress and 6.4 count s^{-1} for the period after the egress (=28.2% of 22.8 count s^{-1}, the total source intensity).

For the after-egress period, the telescope PRF also had to be subtracted. This was done including both the core of the PRF (determined by the intrinsic resolution of the mirror-detector combination) and the mirror scattering. For the core of the PRF, we used an empirical model developed from the data of nearby x-ray sources that are not expected to show dust-scattering halos. For the mirror scattering, the model was derived from the

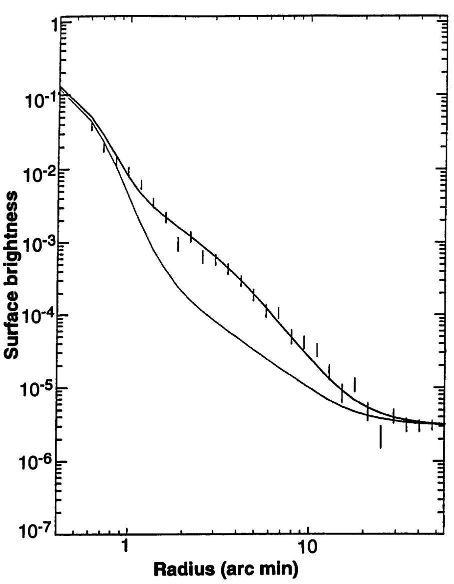

Fig. 4. Plot similar to Fig. 3 but for data from the ROSAT all-sky survey. In this case, the model PRF is averaged over the PSPC field of view. The fractional halo intensity after subtraction of the background is 27.7%.

telescope ground-calibration data. The difference between the measured and the modeled PRF is then considered as a halo around the source generated by the scattering on interstellar dust.

We also analyzed the data of GX 5-1 obtained during the ROSAT all-sky survey (Fig. 4). The resulting halo (fractional intensity = 27.7%) is absolutely consistent with the lunar occultation measurement. As a further proof, the individual count rates for the total flux (22.7 count s^{-1}), the halo flux (6.3 count s^{-1}), and the background count rate (6.8×10^{-5} count s^{-1} arc min^{-2}) within the selected spectral band pass around 1.65 keV are quite similar for all three data sets.

The consistency of the halo properties derived from the pointed observation data before and after egress and from the all-sky survey data demonstrate that the ROSAT telescope with the PSPC due to its very small mirror scattering and low background, respectively, is able to directly image dust-scattering halos and determine the dust properties along the line of sight. This result provides a solid basis for the analysis of the ROSAT all-sky survey data, where dust-scattering halos have been found around essentially every one of the highly absorbed, hard x-ray sources.

The angular extension of a dust-scattering halo is given by λ/a. For an average (spherical) dust grain with radius $a \sim 0.1$ μm and with a ROSAT-typical wavelength $\lambda \sim 10$ Å, the resulting halo sizes are of the order of half a degree. The properties of the grains as well as their spatial distribution can be derived from a halo analysis. For our (simplified) approach, we have fitted our data by single scattering on dust grains with sizes between 0.0003 and 0.3 μm, whereby the size distribution is described by $n(a) \sim a^{-3.5}$ (*7*). The dust is assumed to be distributed uniformly along the line of sight. The resulting scattering optical depth is $\tau \sim 0.3$, implying a dust column density of $\sim 3 \times 10^{10}$ cm^{-2} between GX 5-1 and Earth (*12*).

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12. A more detailed discussion of the dust properties derived from x-ray halo sources as a class will be presented elsewhere (P. Predehl *et al.*, in preparation).

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High-Velocity Pulsars in the Galactic Halo

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It is proposed that high-velocity pulsars are produced in extended galactic halos, and possibly in extragalactic space, from primordial (population III) stars. Such a population of neutron stars could provide an explanation for the gamma-ray bursters and would then accommodate the possibility that most bursters are not in the visible parts of galaxies.

A common origin is proposed for high-velocity pulsars and for gamma-ray bursters. This source is a subdominant population of neutron stars that are in a spatially extended halo around our galaxy. Theoretical speculations and especially recent observations suggest the possible existence of a halo population of neutron stars. Specifically, recent reports of diskward-moving, high-latitude pulsars and of a nearly isotropic distribution of gamma-ray bursters motivate us to propose a source of neutron stars in the halo. We suggest that neutron stars could form by mergers of white dwarfs.

We hypothesize that the halo contains dense clusters of relatively massive white dwarfs that formed at high redshift. Tidal captures and eventual expulsion of a common envelope plausibly produce closely spaced white dwarf binaries whose orbits slowly decay by gravitational radiation. We suggest that the mergers result in optically subluminous events as compared to ordinary supernovae of type I. The neutron stars so formed would have a spatial distribution that is far more extended than the mass profile of the massive dark halo. We identify two signatures of these neutron stars: those formed within the past $\sim 10^7$ years are identifiable as high-velocity radio pulsars, some of which should be approaching the disk for the first time, and the energy stored in the crusts or magnetospheres of the somewhat older neutron stars is released as bursts of gamma rays with a nearly isotropic sky distribution.

Neutron stars are commonly considered to form by massive star collapse and death, culminating in a supernova explosion. The stellar envelope is expelled and the core collapses to form a neutron star, detectable as a radio pulsar or as an x-ray binary. Neutron stars should therefore form in the galactic disk. In a somewhat different context, it has been suggested that a component of halo dark matter plausibly consists of dark baryonic matter in the form of compact stellar remnants, which might include brown dwarfs and white dwarfs, or even some neutron stars and black holes, that formed in the early stages of galactic evolution (*1*). It is this hypothesized halo population of compact stellar remnants that provides a source, by white dwarf mergers, of young neutron stars.

It has recently been reported (*2*) that, among a sample of 44 high galactic latitude pulsars, many are moving toward the galactic disk, apparently originating in the halo. This result is surprising at first because fresh neutron star production is traditionally thought to require fresh star formation and supernovae. Inasmuch as neither of these processes is thought to be taking place in the halo, it would then follow that the production of fresh neutron stars in the halo, the simplest interpretation of the observations, is similarly unlikely. In this report, we suggest that high-velocity pulsars are copiously produced in dark populations by white dwarf coalescence, which would

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