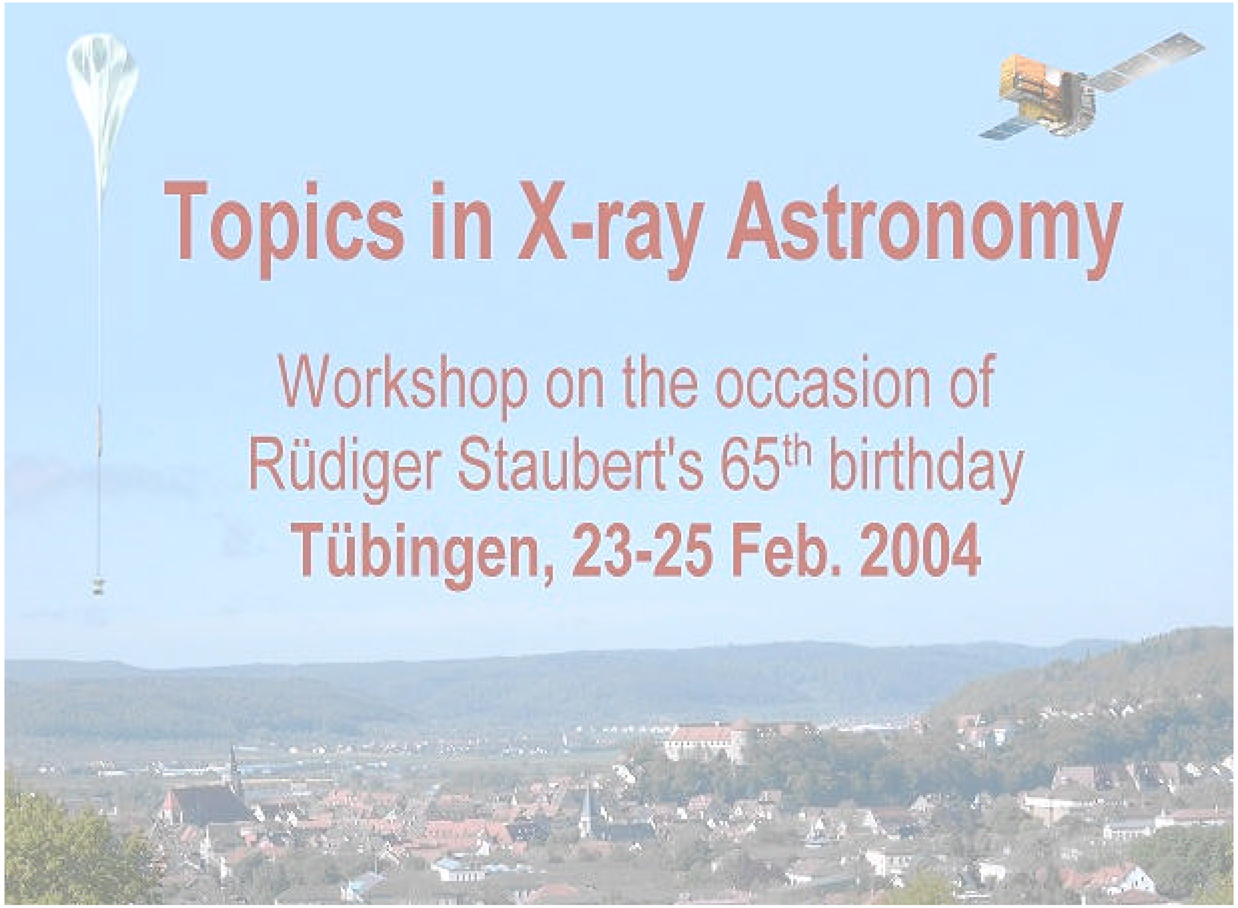
The Story of

Dust Scattering Haloes

(Röntgenstreuung an Interstellarem Staub)

Peter Predehl

Max-Planck-Institut für extraterrestrische Physik



SMALL-ANGLE SCATTERING OF CELESTIAL X-RAYS BY INTERSTELLAR GRAINS*

James W. Overbeck
Physics Department and Center for Space Research
Massachusetts Institute of Technology, Cambridge 39, Massachusetts
Received November 3, 1964

ABSTRACT

The theory of scattering of X-rays by grains is reviewed, and it is shown that in typical situations a measurable fraction of celestial X-rays will have been scattered. This will appear observationally as an increase in the apparent angular width of celestial X-ray sources.

Recently celestial X-ray sources of unexpected intensity have been discovered (Giacconi, Gursky, Paolini, and Rossi 1962, 1963; Bowyer, Byram, Chubb, and Friedman 1964), and it has been suggested that some of them may be neutron stars. These would appear as point sources in orbiting X-ray telescopes now being built. It is the purpose of this paper to point out that if neutron stars exist their images will yield valuable information about interstellar grains. The grains will scatter some of the X-rays, typically by 1′ to 1°, making a point source appear to be surrounded by a diffuse source. An appreciable fraction of the X-rays can be in the diffuse component, as one can see by comparing the cross-section for small-angle scattering with that for optical extinction, which is roughly the geometrical cross-section of a grain.

Theoretical Approach

(no instrument available)

1965 Overbeck, J.W. 1965 *Ap.J.* **141**, 864

1969 Slysh, V.I. 1969, *Nature* **224**, 159

1970 Hayakawa, S. 1970, *Prog. Theor. Phys.* **43**, 1224

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1970 Martin, P.G. and Sciama, D.W. 1970, *Ap.Letters* **5**, 193

1973 Trümper, J. And Schönfelder, V. 1973, *Astr. Ap.* **25**, 445

1975 Spitzer, L. and Jenkins, E.B. 1975, *Ann. Rev. Astr. Ap.* **13**, 133

1975 Spiegelhauer, H. and Trümper, J. 1975, *J. Brit. Interplanetary. Soc.* **28**, 319

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1977 Mathis,J.S., Rumpl,W., Nordsieck, K.H., 1977, *Ap.J.* **217**, 425

1978 Martin, P.G. 1978, *Cosmic Dust* (Oxford: Clarendon)

1978 Alcock, C. and Hatchett, S. 1978, *Ap.J.* **222**, 456

1979 Mathis, J.S. 1979, *Ap.J*. **232**, 747

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1983 Norwell,G., Evans,A., Bode,M.F. 1983, *Nature* **303**, 49

Astron. & Astrophys. 25, 445–450 (1973)

Distance Determination of Variable X-ray Sources

J. Trümper
Astronomisches Institut der Universität Tübingen

V. Schönfelder
Max-Planck-Institut für Extraterrestrische Physik Garching bei München

Summary. A new method is described for the direct determination of the geometric distance of X-ray sources. The method is applicable to variable X-ray sources and implies the existence of an X-ray halo, which is formed by scattering on interstellar dust. Time structures are delayed and smeared out in the halo. Since the time scales involved depend linearily on the source distance the latter can be determined by measuring damping effects across the halo. Also, information can be obtained about the dust density distribution along the line of sight.

Key words: X-ray astronomy – variable X-ray sources – source distances – interstellar dust.

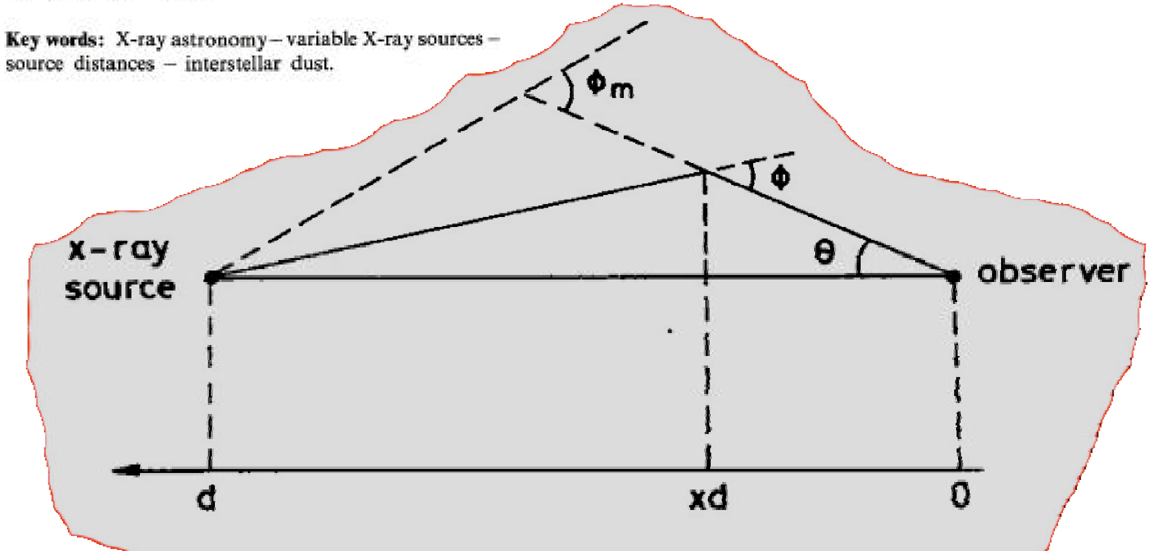
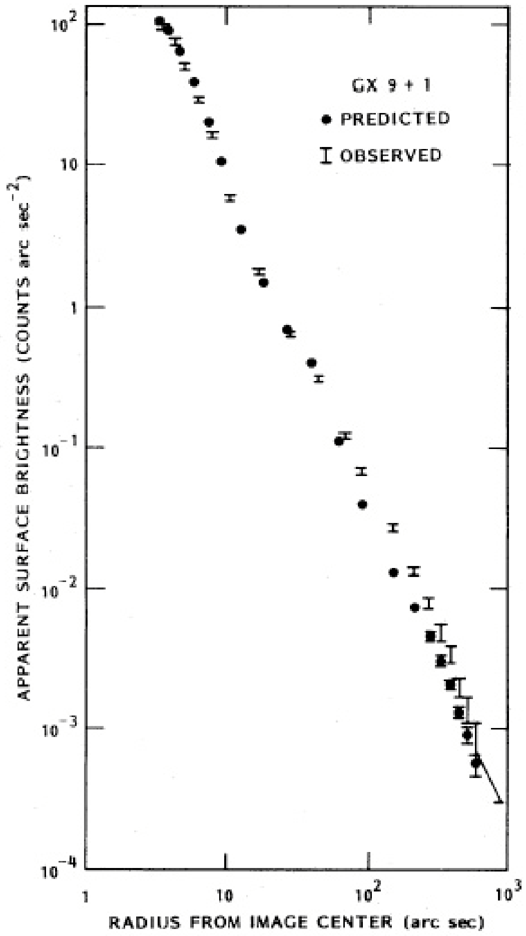


Fig. 1. Illustration of geometries

Einstein Observatory



comparing radial surface brightness distribution with instrument‘s point response function

"competitor": microroughness of mirror system leads to instrumental halo

Evidence for detection of dust halos has been obtained by comparing the apparent surface brightness in images of four low-latitude galactic center sources with the surface brightness predicted from the telescope point response function and the simultaneously measured source spectra.

TABLE 1

X-RAY SOURCE CHARACTERISTICS

Source	Galactic Latitude	Line of Sight in Dust Lane (kpc)	Hydrogen Column Density (cm^{-2})	Measured Fraction of X-Rays in Halo
GX 13+1 (4U 1811−17)	0°08	>10	1.5×10^{22}	0.18±0.02
GX 3+1 (4U 1744−26)	0.83	6.9	7×10^{21}	0.19±0.01
GX 9+1 (4U 1758−20)	1.15	5.0	7×10^{21}	0.13±0.01
GX 17+2 (4U 1813−14)	1.28	4.6	8×10^{21}	0.21±0.01
GX 9+9 (4U 1728−16)	9.03	0.6	1.7×10^{21}	0.03±0.01
LMC X−3 (4U 0538−64) ...	−32.05	0.2	6×10^{20}	...

THE ASTROPHYSICAL JOURNAL, 302:371–387, 1986 March 1

MEASUREMENTS OF X-RAY SCATTERING FROM INTERSTELLAR GRAINS

CHRISTOPHER W. MAUCHE AND PAUL GORENSTEIN
Harvard-Smithsonian Center for Astrophysics
Received 1985 April 9; accepted 1985 September 4

ABSTRACT

We report on the results of an *Einstein Observatory* imaging proportional counter investigation of the halos produced by the scattering of X-rays from interstellar grains of four compact Galactic (low-latitude) and two extragalactic (high-latitude) X-ray sources. We find that the intensity of these halos correlates well with (1) the amount of visual extinction and (2) the distance through the Galaxy's dust layer: quantities which measure the column density of grains to a given source. From this result, and from the size and shape of the halos from the Galactic sources, we are able to derive a number of grain parameters in the context of two alternate grain size distributions: the Mathis-Rumpl-Nordsieck (MRN) and the Oort–van de Hulst distributions, either of which is capable of producing the observed halos. Though no single grain size is capable of producing the shapes observed for these halos, a mean size of $\sim 0.1\ \mu m$ and a number density of $\sim 10^{-12}$ grains cm^{-3} produce the correct halo intensities. From the additional parameters determined from the size and shape of the halos, we find results concerning the amount of material in grains which are in general agreement with the observed depletion of the elements from the gas phase of the interstellar medium, as well as with the detailed predictions of the MRN size distribution.

Subject headings: interstellar: grains — X-rays: sources

Rayleigh-Gans approximation +
"Gaussian form factor":

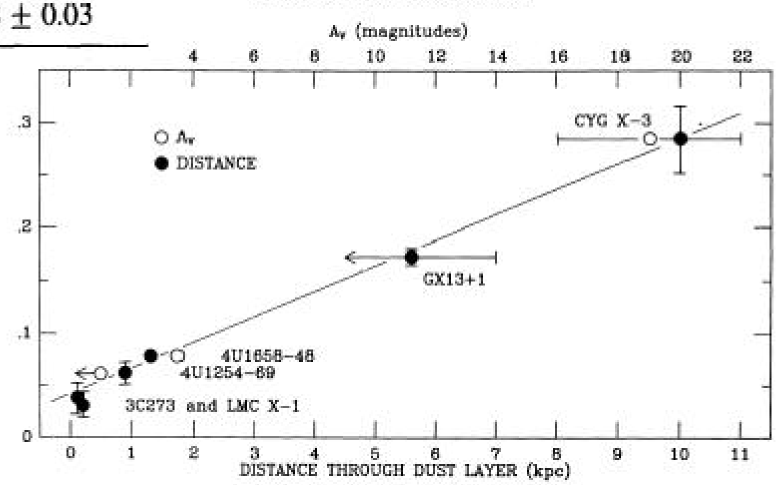
$$\frac{d\sigma_{scat}}{d\Omega} = 1.1 \times 10^{-6}\left(\frac{2Z}{M}\right)^2\left(\frac{\rho}{3}\right)^2 a(0.1\ \mu\mathrm{m})^6\left[\frac{F(E)}{Z}\right]^2 \exp\left(-\frac{\theta_{scat}^2}{2\tilde{\sigma}^2}\right)\ \mathrm{cm}^2\ ,$$

$$\sigma_{scat} = 6.3 \times 10^{-11}\left(\frac{2Z}{M}\right)^2\left(\frac{\rho}{3}\right)^2 a(0.1\ \mu\mathrm{m})^4 E(\mathrm{keV})^{-2}\left[\frac{F(E)}{Z}\right]^2\ \mathrm{cm}^2\ .$$

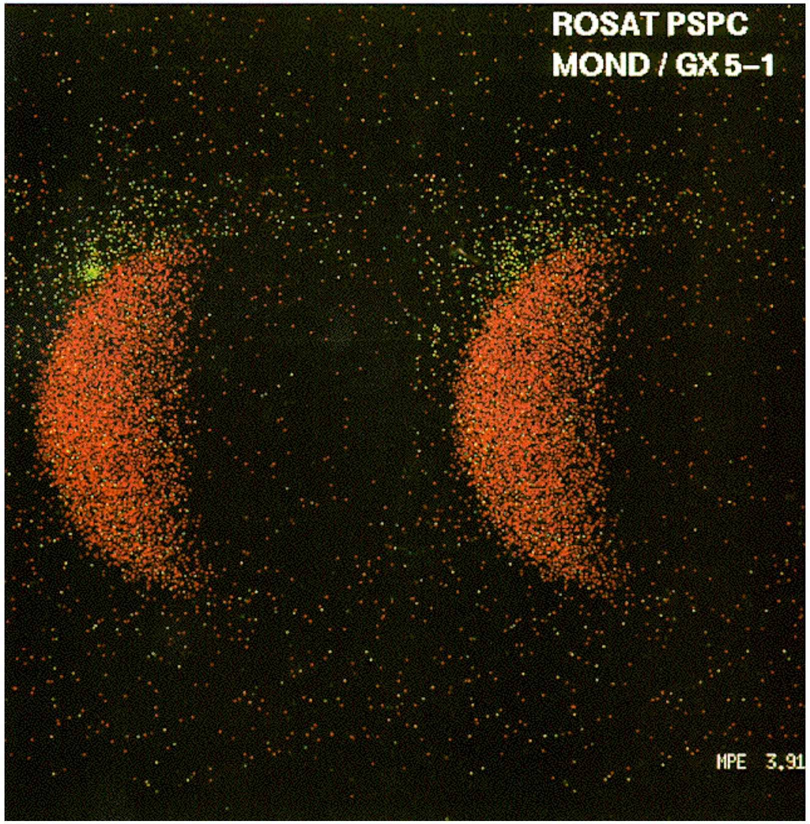
$\sigma_{scat} \sim a^4\ E^{-2}$ $\delta\sigma/\delta\Omega \sim \exp(-\ a^2\ E^2\ \Theta^2)$

Source	l	b	A_v[a] (mag)	d (kpc)	Fractional Halo Intensity[b]
3C 273	290°	+64°.5	...	0.11[g]	0.04 ± 0.02
LMC X-1	280	+31.5	...	0.19[g]	0.03 ± 0.01
4U 1254−69	304	−6.4	<1	0.90[g]	0.06 ± 0.01
4U 1658−48	339	−4.3	3.5	1.33[g]	0.078 ± 0.003[h]
GX 13+1	13.5	+0.1	?	<5.6[i]	0.17 ± 0.01[j]
Cyg X-3	79.9	+0.7	19	10^{+1}_{-2}[k]	0.28 ± 0.03

MAUCHE AND GORENSTEIN



ROSAT (1991)

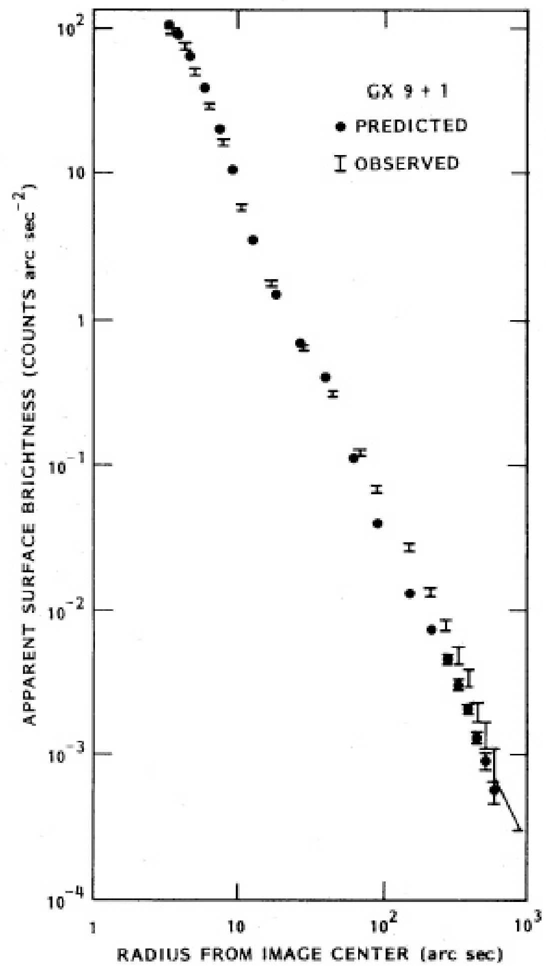


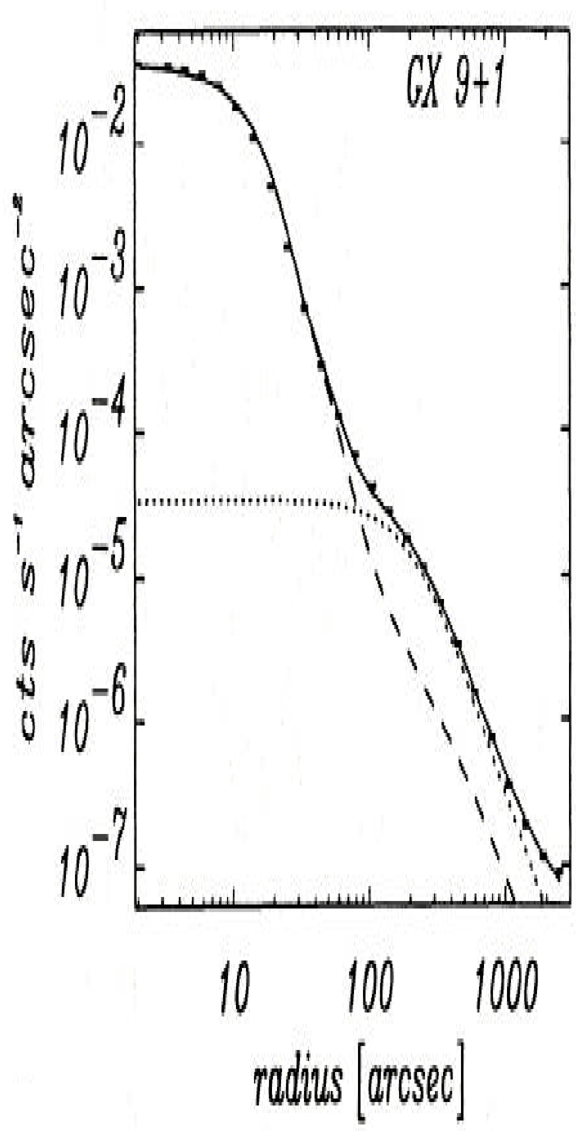
"experimental" separation between mirror and dust scattering:

Lunar occultation of GX 5-1

Predehl et al. 1992, *Science* **257**, 935

Einstein ? ROSAT





Astron. Astrophys. 293, 889–905 (1995)

ASTRONOMY
AND
ASTROPHYSICS

X-raying the interstellar medium: ROSAT observations of dust scattering halos

P. Predehl and J.H.M.M. Schmitt[1]

[1] Max-Planck-Institut für extraterrestrische Physik, D-85740 Garching bei München, Germany

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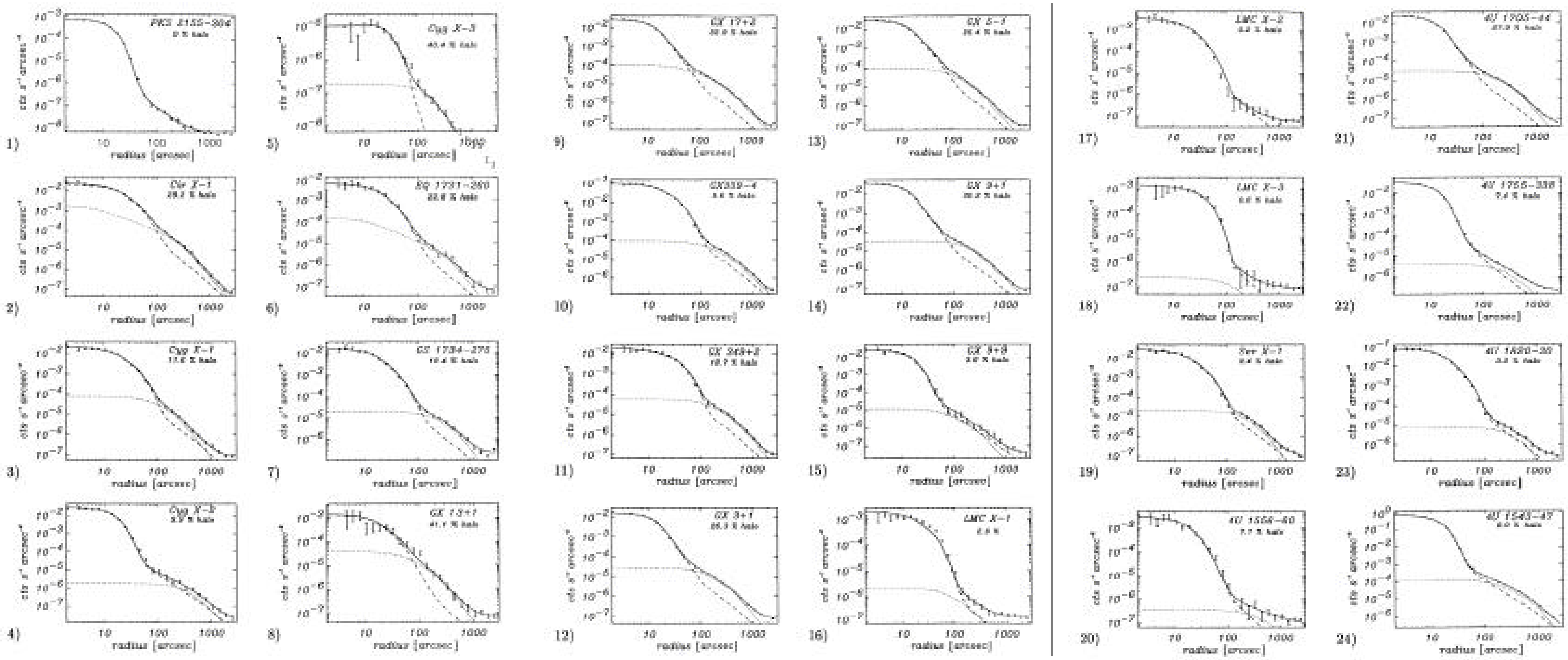
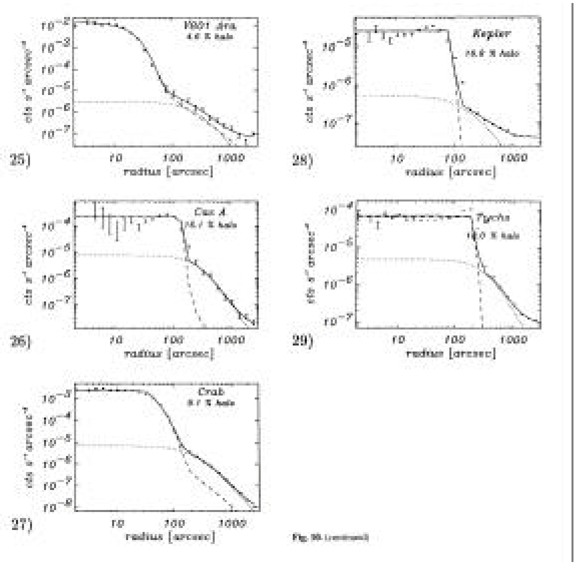
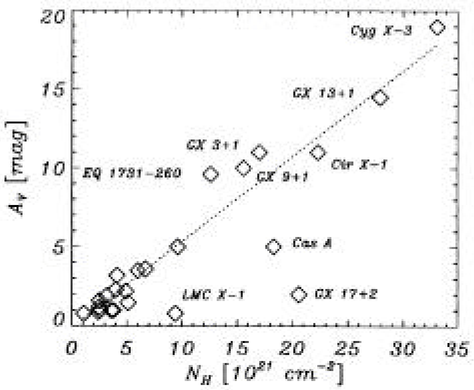
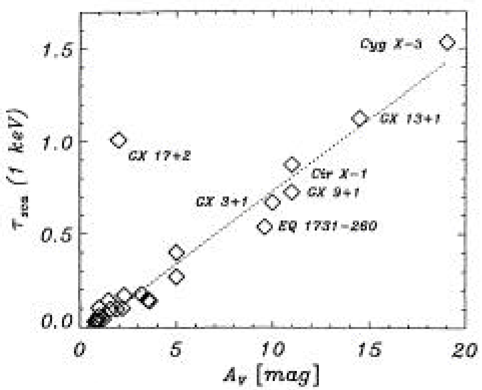
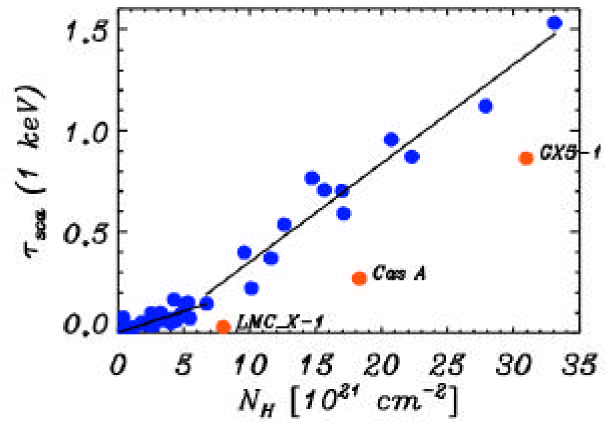




Largest sample of haloes so far…







ISM: $A_V \sim N_H \sim \tau_{sca}$

interstellar material ? local material

physical properties of grains: fluffiness ?

1998: End of ROSAT era

One X-ray source never been observed with an imaging telescope

Still a white spot in ROSAT all-sky survey…

[redacted]

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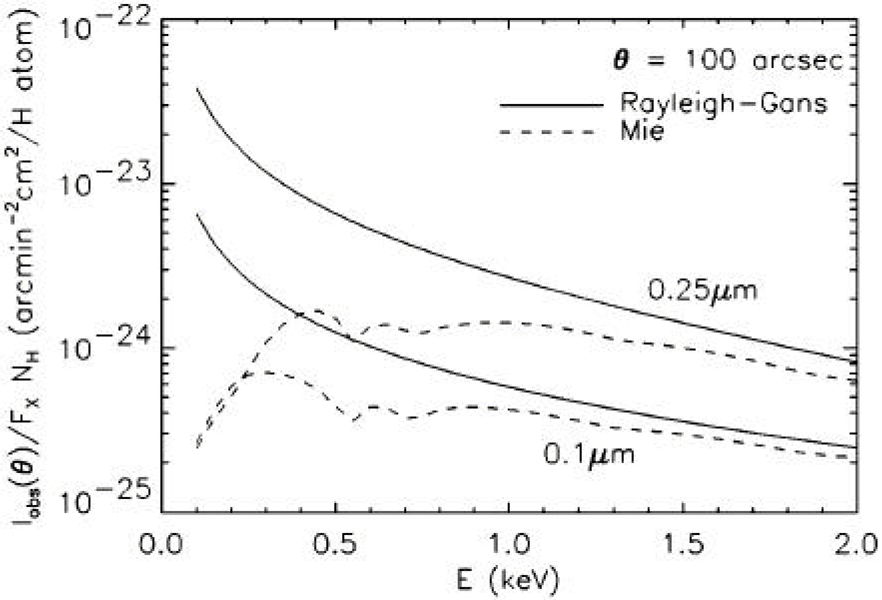
SOFT X-RAY SCATTERING AND HALOS FROM DUST

RANDALL K. SMITH[1] AND ELI DWEK
NASA Goddard Space Flight Center, Code 685, Greenbelt, MD 20771
Received 1997 October 22; accepted 1998 March 27

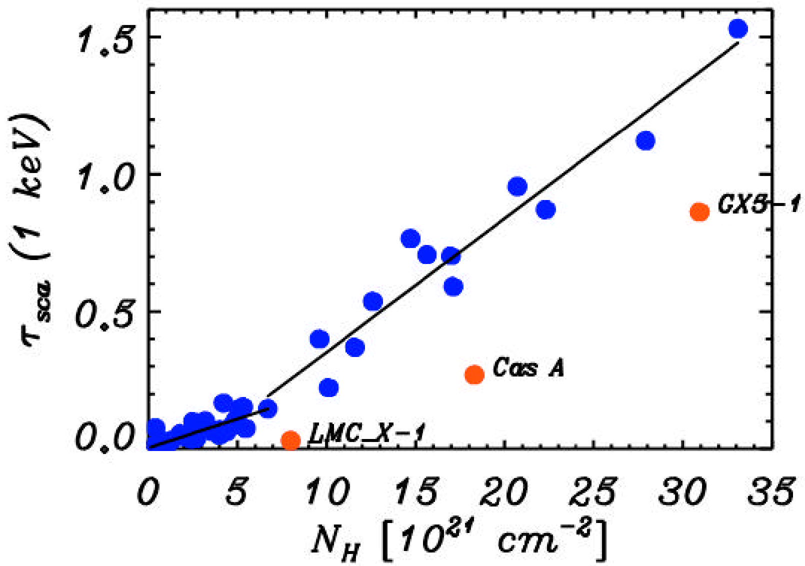
ABSTRACT

Small-angle scatterings of X-rays by interstellar dust particles create halos around X-ray sources. The halo intensity and its projected radial distribution around a source can provide important information on the spatial distribution of the dust along the line of sight to the source and on the physical properties of the scattering dust particles. Halos around X-ray point sources have been used by several authors to infer that the scattering dust particles are fluffy in nature, consisting of aggregates of smaller refractory particles with vacuum occupying a significant fraction of their volume. The nature and morphology of interstellar dust particles has recently gained new importance, since fluffy, composite dust particles have been suggested as a possible solution to the interstellar carbon "crisis." This crisis results from the discrepancy between the abundance of carbon in the interstellar medium available for creating dust and the significantly larger amount of carbon that must be in dust in order to account for the UV-optical interstellar extinction in the diffuse ISM. Previous studies of X-ray scattering have used the Rayleigh-Gans (RG) approximation to the differential scattering cross section to calculate halo properties. However, the validity of the RG approximation fails for energies below 1 keV. We use the exact Mie solution for the differential scattering cross section and find that, for these energies, the scattering becomes much less efficient than is predicted by the RG approximation. Furthermore, the effects of K and L shell absorption by atoms in the dust become important. The net effect is that the RG approximation systematically and substantially overestimates the intensity of the halo below 1 keV, relative to the Mie solution result. In particular, Mathis and coworkers used the weaker than expected halo intensity observed around Nova Cygni 1992 to conclude that interstellar dust must be fluffy. Using the Mie solution to the scattering intensity and including the effects of absorption, we find that, contrary to the conclusion of Mathis and coworkers, the halo around Nova Cygni 1992 does not *require* interstellar dust grains to be fluffy in nature and that the data are consistent with scattering from a mixture of bare refractory silicate and carbon grains as well.

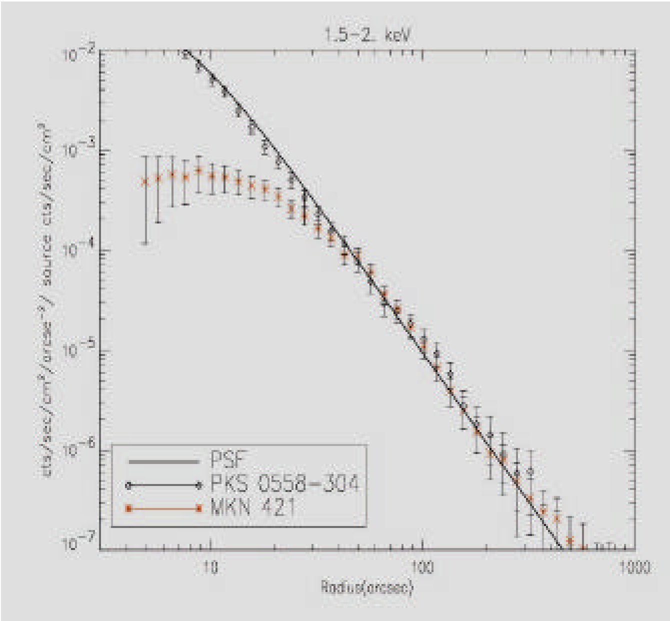
Validity of Rayleigh-Gans Approx.



$$k_0\, a\, |m - 1| \ll 1$$



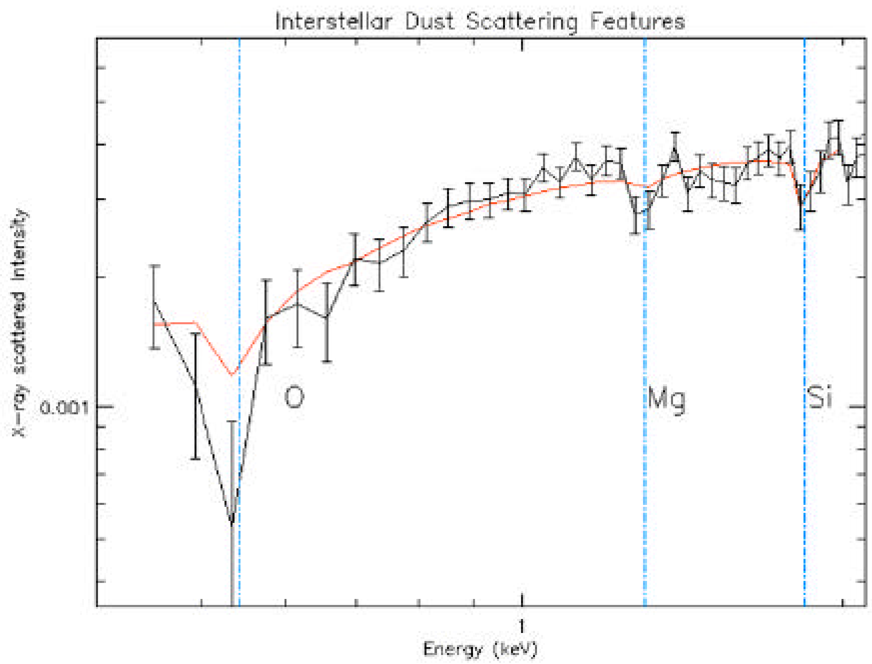
2000: Chandra & XMM-Newton



Improved spectral resolution

However: pileup

First Detection of Scattering Features



Modelling yields

olivines $Fe_{2-x}Mg_xSiO_4$

pyroxenes $Fe_{1-x}Mg_xSiO_3$

Costantini et al. 2004

Chandra measurement of the geometrical distance to Cyg X-3 using its X-ray scattering halo

P. Predehl[1], V. Burwitz[1], F. Paerels[2], and J. Trümper[1]

[1] Max-Planck-Institut für Extraterrestrische Physik, Giessenbachstrasse, 85748 Garching, Germany (predehl@mpe.mpg.de)
[2] Columbia University, New York, USA

Received 24 March 2000 / Accepted 8 April 2000

Abstract. Using Chandra-HETGS data of Cyg X-3 we succeeded for the first time in applying a method, developed 27 years ago, to directly determine the geometric distance to X-ray sources. The method implies the existence of a halo of radiation scattered on interstellar dust. Any intensity variations of the source itself appear delayed and smeared out in the halo. By analysing and correlating the X-ray lightcurves at different radial distances from the source, we could determine the distance to Cyg X-3 to be approximately 9 kpc. Even though the statistics in this dataset are meager the usefulness and the possibilities of this method are convincingly demonstrated.

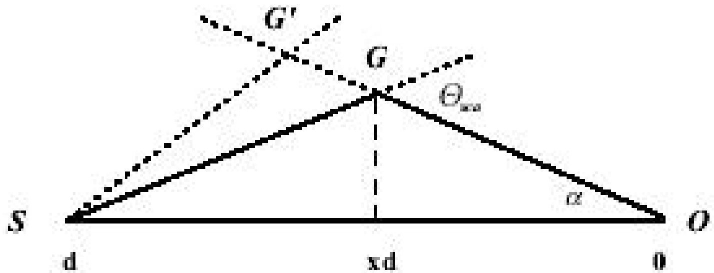
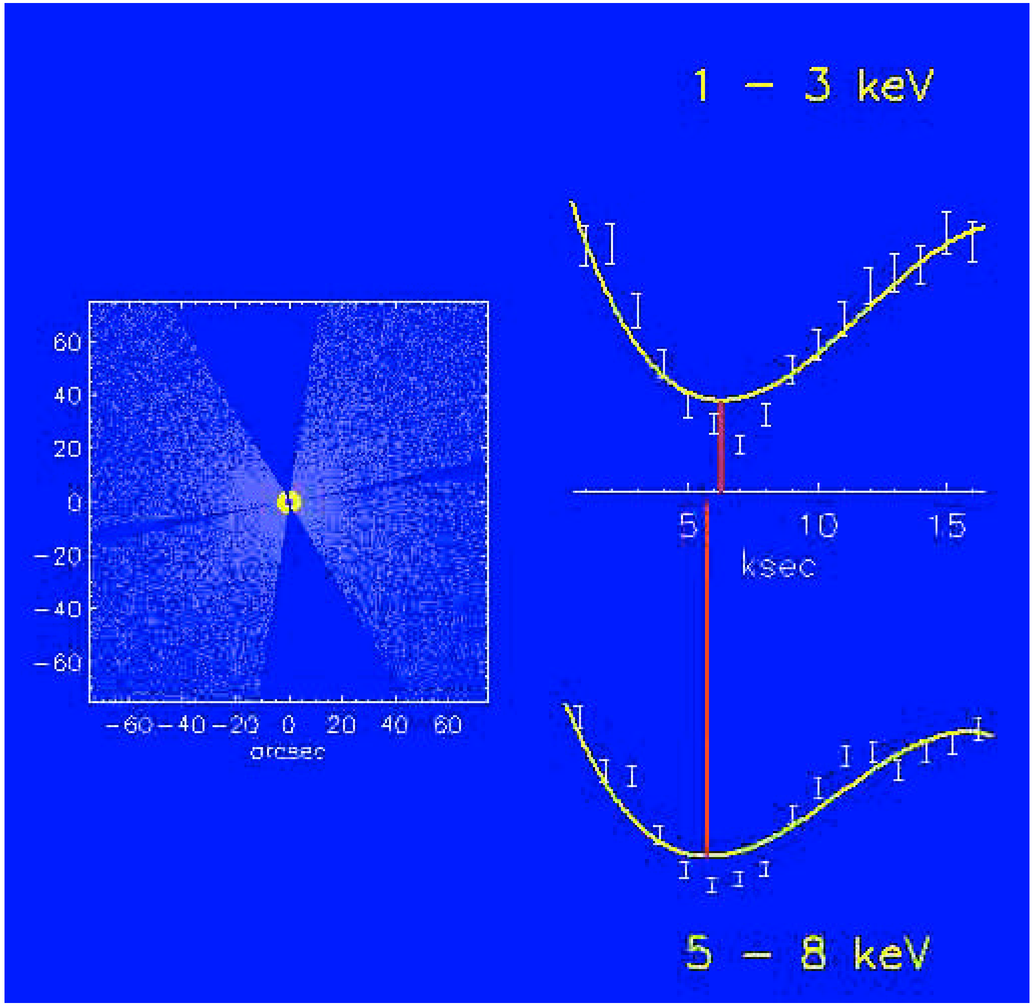


Fig. 1. Scattering geometry

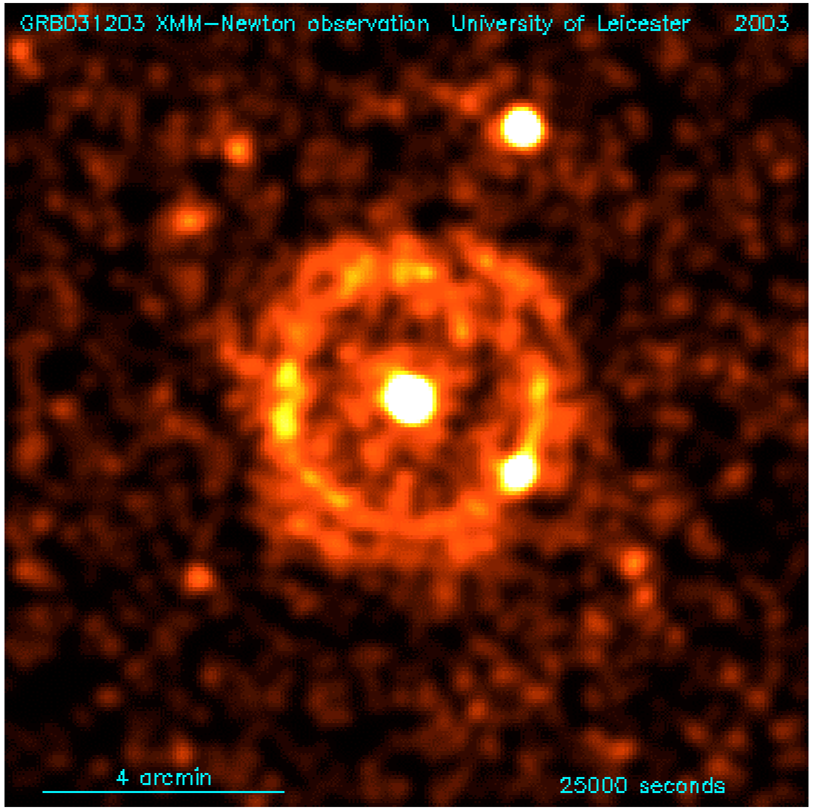


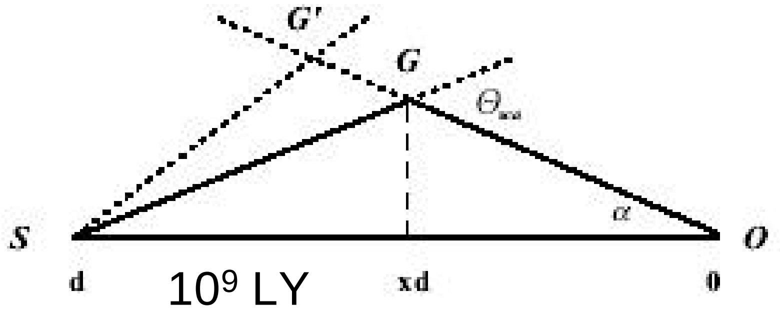
Cyg X-3

$d = 8.4^{-0.4}_{+0.6}$ kpc

XMM-Newton

Expanding Galactic X-ray halo around GRB 031203





xd_1 = 2900 LY (Gum Nebula)
xd_2 = 4500 LY

Vaughan et al. 2004