Mapping the Hot ISM Using X-Ray Shadowing Towards Infrared Dark Clouds

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ABSTRACT

We made an X-ray shadowing experiment toward the infrared dark cloud (IRDC) G28.4+0.1 using *XMM-Newton* (OBSID 0302970301). X-ray shadowing is the only known method of determining the distribution of hot plasma in the plane of the Milky Way. IRDCs are ideal X-ray shadowing targets due to their very high column densities (~10^{21} - 10^{23} cm^{-2}) and the fact that their distances can be derived from HI self-absorption studies and morphological matches with molecular gas. Our pilot study of three IRDCs focuses on clouds near 30° Galactic Longitude that have distances 3 to 5 kpc from the Sun. Here we focus on the best shadowing candidate of our pilot study, IRDC G28.4+0.1 which is ~5 kpc from the Sun. We are planning a larger X-ray shadowing survey that will cover multiple sky positions and map molecular clouds at varying distances along neighboring lines of sight. These data will allow us to determine the three-dimensional distribution of hot plasma in the Galactic plane. Such a map of the hot gas distribution will provide important information about the evolution of the interstellar medium and help constrain the energy balance and chemical evolution of our Galaxy.

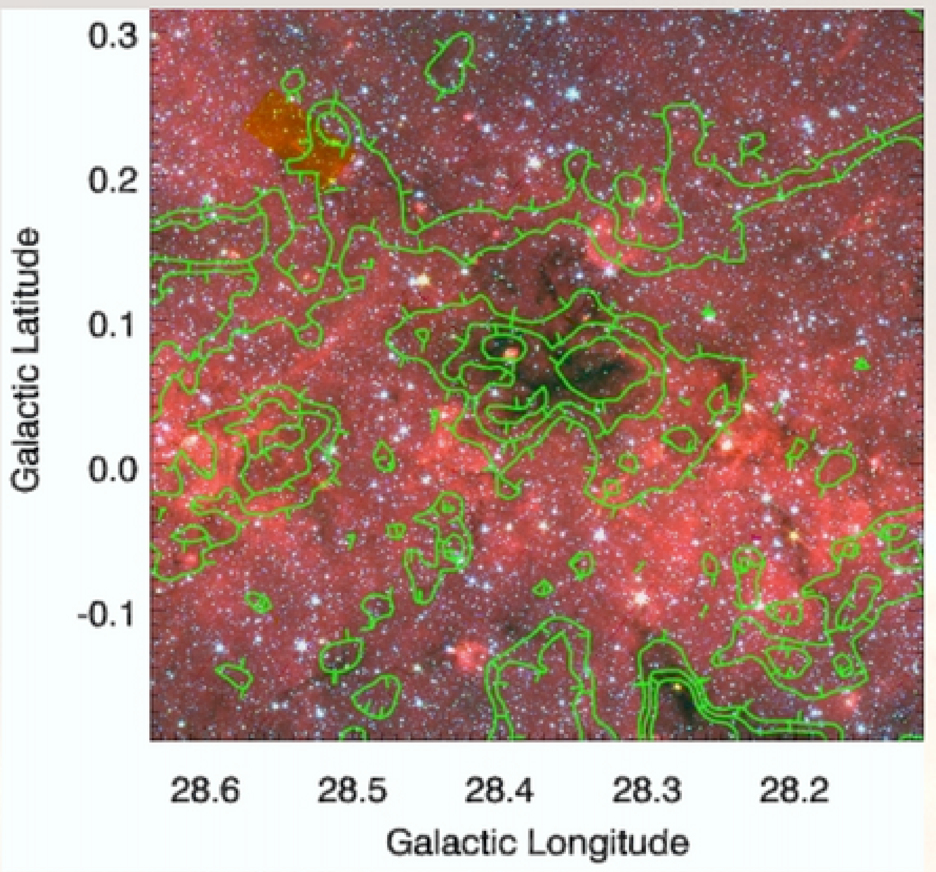


Figure 1 – GLIMPSE three color image of 3, 4 and 8 □m data showing the IRDC G28.4+0.1 at center. Contours are of ^{13}CO about 78.6 km s^{-1} and show the excellent morphological match. The image is approximately the size of the *XMM* field of view.

IRDCs

Infrared Dark Clouds (IRDCs) are very dense clouds that are dark at infrared wavelengths. They were first seen in *MSX* 8 □m data, and are a ubiquitous feature in the higher resolution Galactic Legacy Infrared Mid-Plane Survey Extraordinaire (GLIMPSE; Benjamin, 2003). Figure 1 is a three color GLIMPSE image (red = 8□m, green = 4μm, blue = 3μm) of our target cloud G28.4+0.1. The contours in Figure 1 are of ^{13}CO from the Galactic Ring Survey (GRS; Jackson et al., 2006). The size of the image is approximately the same as the *XMM* field of view. G28.4+0.1 clearly has high IR extinction, takes up a significant fraction of the *XMM* field of view, and has a high molecular column density. Because of the clean morphological match between ^{13}CO and IR extinction, we know G28.4+0.1 lies ~5 kpc from the Sun. The dense IRDC material is absorbing background IR radiation so the cloud is at the near kinematic distance given by the CO velocity.

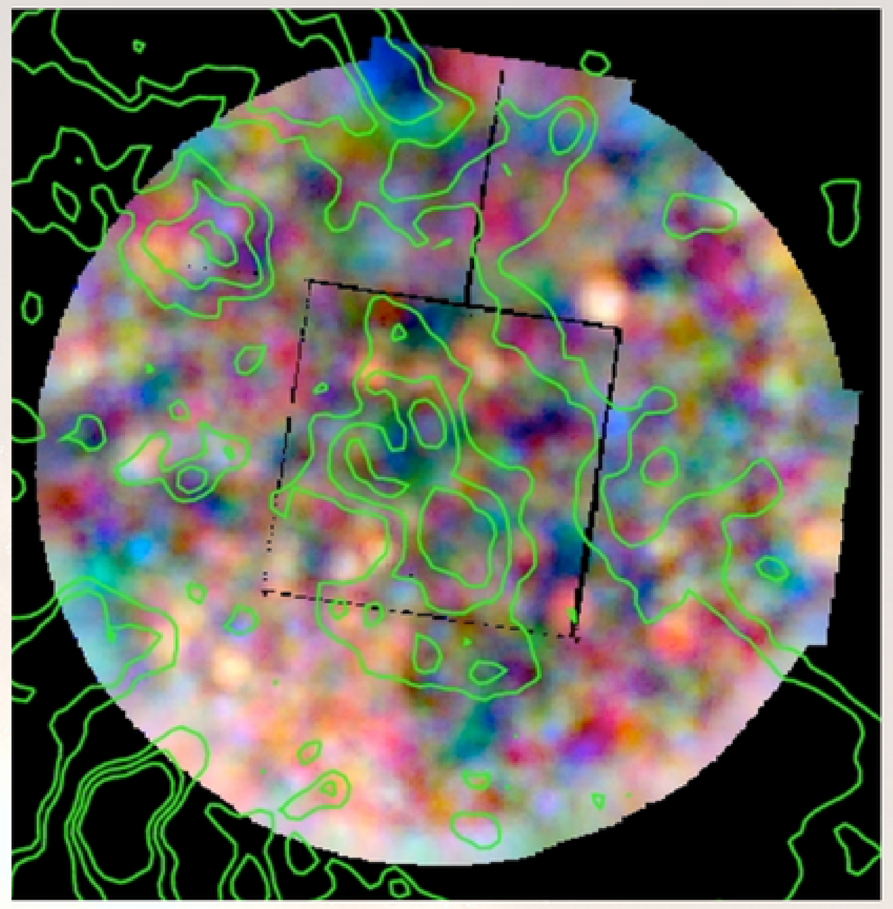


Figure 2 – *XMM* three color image in the bands 0.4-1.25 keV, 1.25-2 keV and 2-8 keV with ^{13}CO contours overlaid. There is no clear correlation between molecular column and X-ray deficit.

DATA REDUCTION AND IMAGING

Using the *XMM* Extended Source Analysis Software (*XMM-ESAS*), we first filtered the events file for periods of high soft proton contamination. The light curve of G28.4+0.1 is unusually steady, indicating minimal contamination. Figure 2 shown a three color image of three energy bands: 0.4–1.25 keV (red), 1.25–2.0 keV (green) and 2.0–8.0 keV (blue). For each band we modelled any residual soft proton contamination as well as the particle background and subtracted these from the data. Each resulting band image was smoothed and all three were combined to make Figure 2. There is in general no correlation between high column density and low intensity in the 0.4–1.25 keV band; **we see no evidence for an X-ray shadow in the images.** Spectral analysis was needed to determine why this cloud produced no shadow.

STRATEGY

We use the *XMM-ESAS* to create four spectra for the G28.4+0.1 observations: *ON*- and *OFF*-cloud spectra for the MOS1 and MOS2 detectors (*XMM-ESAS* does not yet process PN data). Our procedure relies on the accurate estimation of the total column density (molecular and atomic) in front of and behind the cloud for both *ON*- and *OFF*-cloud directions. We include the cloud column density in the behind cloud numbers.

ESTIMATION OF COLUMN DENSITY

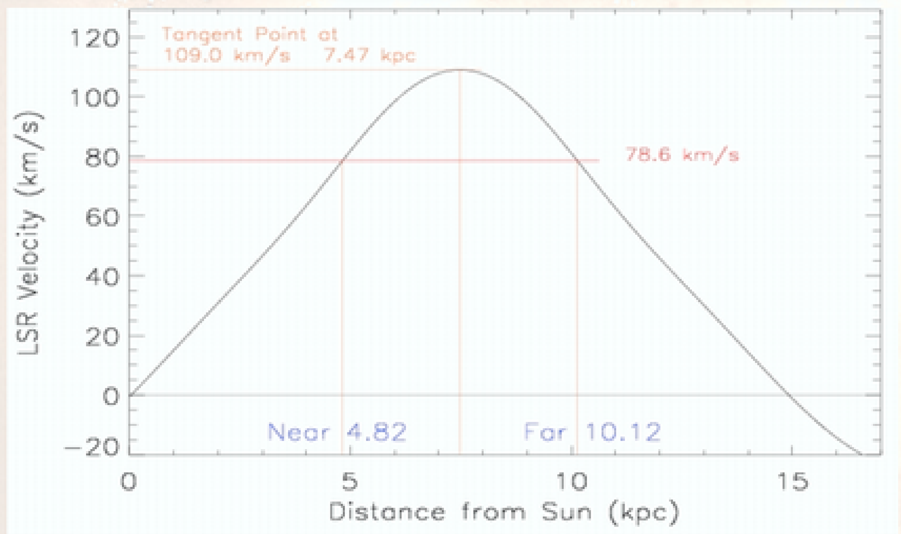
Molecular: We used GRS ^{13}CO data to estimate the molecular column density. Figure 3 shows that gas at velocities up to the 78.6 km s^{-1} IRDC velocity could be at either the near or far kinematic distance, whereas the gas at velocities greater than the cloud velocity is beyond the cloud. We computed an average integrated intensity in front of and behind the cloud then converted this ^{13}CO integrated intensity to H_2 column density using the Simon et al. (2001) procedure.

Atomic: We used the 21 cm HI VLA Galactic Plane Survey (VGPS; Stil et al., 2006) to estimate the atomic column density assuming a spin temperature of 150K. The distribution of gas along the line of sight was determined in the same manner as for the molecular data.

Our results in units of 10^{22} cm^{-2} are shown below.

		N(HI)	N(H_2)	N_T = N(HI) + 2N(H_2)
ON-cloud	In Front	0.5	0.25	1.0
	Beyond	1.0	2.0	5.0
OFF-cloud	In Front	0.5	0.25	1.0
	Beyond	1.0	1.0	3.0

Figure 3 - LSR velocity vs. distance from the Sun relation for IRDC 28.4+0.10 assuming the Clemens (1985) Galactic rotation curve.



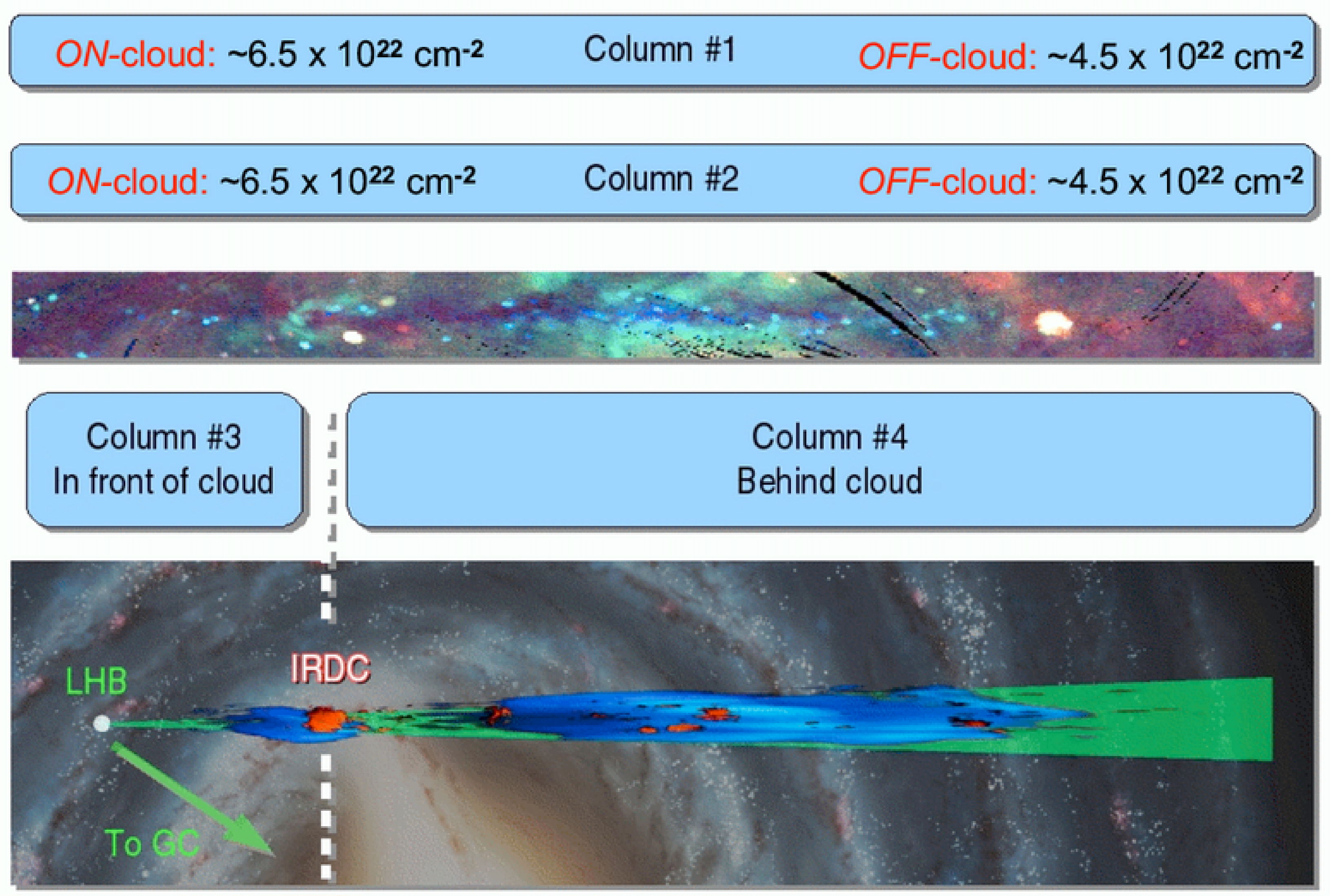


Figure 4 – Components of our spectral modelling affected by the Galactic column density. In the lowest image, molecular gas from the GRS is shown in red while atomic gas from the VGPS is shown in blue. The Local Hot Bubble (labeled LHB), the direction of our observation (green wedge), and the direction towards the Galactic center are also shown. The size of the wedge and the LHB are slightly exaggerated for clarity. IRDC G28.4+0.1 is associated with a large dense molecular cloud 5 kpc from the Sun.

SPECTRAL MODELLING

We used XSPEC V11.0 to model the X-ray background with the following components illustrated in Figure 4:

1) A power law with a photon index of 1.46 from unresolved AGN.
2) A hot (few keV) absorbed thermal component from the Galactic ridge emission.
3) A cool (~1 keV) absorbed thermal component from Galactic emission along the line of sight . It is the distribution of this component which we are determining.
4) A 0.11 keV (fitted value) thermal Local Hot Bubble (LHB) component.

In addition, there are two sources of contamination in our spectra: the instrumental lines near 1.5 keV and a residual soft proton component not removed through time filtering. We modelled the instrumental lines as Gaussians and the soft proton component as a power law not folded through the instrumental response.

We created four spectra: *ON*- and *OFF*-cloud spectra for the MOS1 and MOS2 detectors and used the HEASARC X-ray background tool to extract a ROSAT spectrum from the same direction. The ROSAT data constrained the soft components of the model and we linked parameters where physically reasonable. Our results are shown in Figure 5. **Within the statistical errors, we see no evidence for shadowing of the cooler component**. **This strongly implies that the observed emission originates foreground to the cloud.** In Figure 6 we plot the MOS1 data with the normalization adjusted to show that *ON*- and *OFF*-cloud models are basically identical.

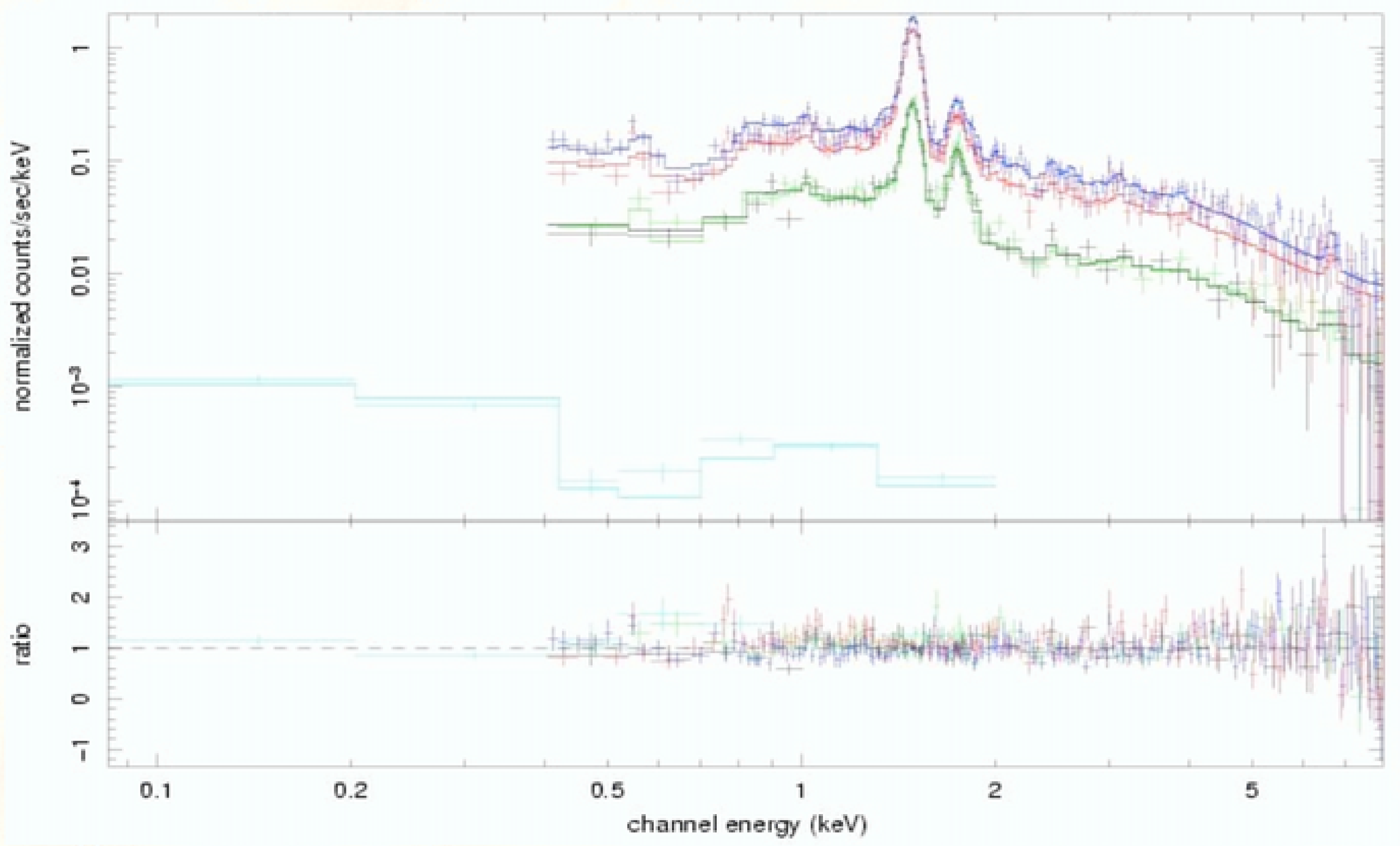


Figure 5 – Our five spectra and fitted models. ROSAT data are shown in light blue, *ON*-cloud data in black (MOS1) and green (MOS2), and *OFF*-cloud data are shown in red (MOS1) and blue (MOS2). The fit is quite good, with a reduced □^{2} value of 1314.9/1240 = 1.06

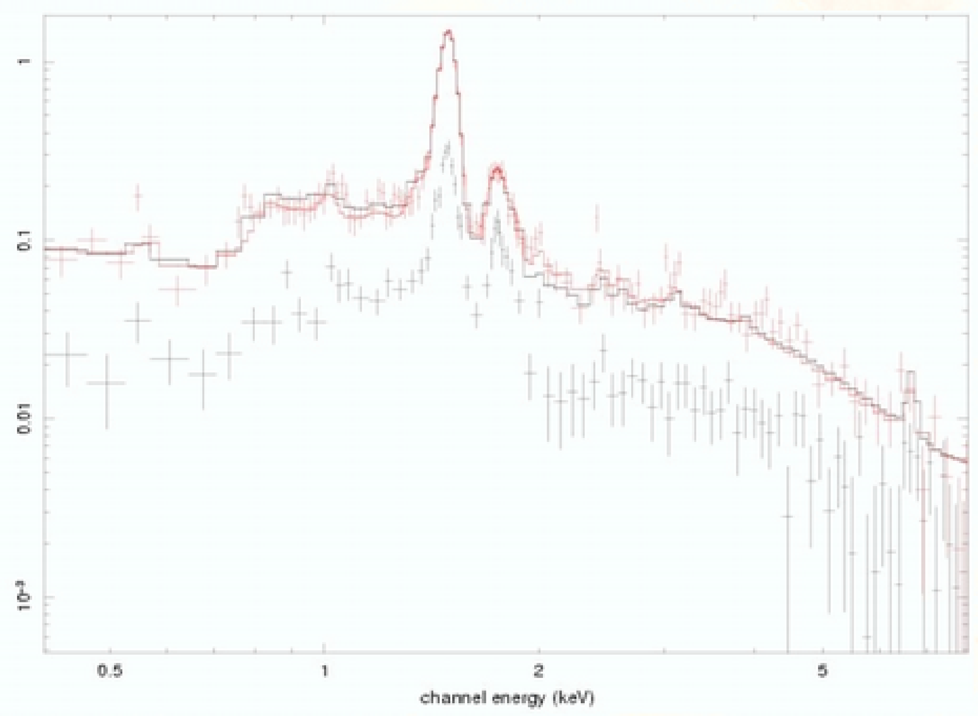


Figure 6 – MOS1 spectra with the same models as are shown in Figure 5, but the normalization has been adjusted upwards for the *ON*-cloud spectra to show the similarity between the *ON*- and *OFF*-cloud models. The *ON*-cloud model is shown in black while the *OFF*-cloud model is shown in red.

SUMMARY

The HI and CO data allow us to determine the total atomic and molecular column densities for both *ON*- and *OFF*-cloud directions. G28.4+0.1 has a very high column density:~4 x 10^{22} cm^{-2}. This amount of column should absorb much of the X-ray flux in the ¾ keV band. Nonetheless spectral fits show that this cloud is not producing appreciable X-ray absorption. **We conclude that the cooler diffuse X-ray background must originate in front of G28.4+0.1, from a region within ~5 kpc of the Sun.** More observations are necessary to further constrain the distribution of emission within this limit.

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