Investigating Galactic Dust Using the X-ray Dust-scattering Echo of GRB 221009a

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What if there was a way to directly calculate the distance to dust clouds?

Using X-ray dust tomography, we conduct a preliminary analysis of the GRB 221009a light echo to measure the distribution of interstellar dust with high accuracy. We also pair X-ray observations with CO measurements to identify associated clouds of dust and molecular gas and contextualize them in the Galactic environment.

X-ray Dust Tomography

When an X-ray source undergoes a bright and temporally well-defined outburst, dust grains cause X-ray photons to scatter preferentially in the forward direction. The X-ray signal then appears as a **light echo**, or a series of concentric rings where each ring is representative of an intervening dust layer. This allows us to study the distribution of interstellar dust in the Milky Way in exquisite detail.

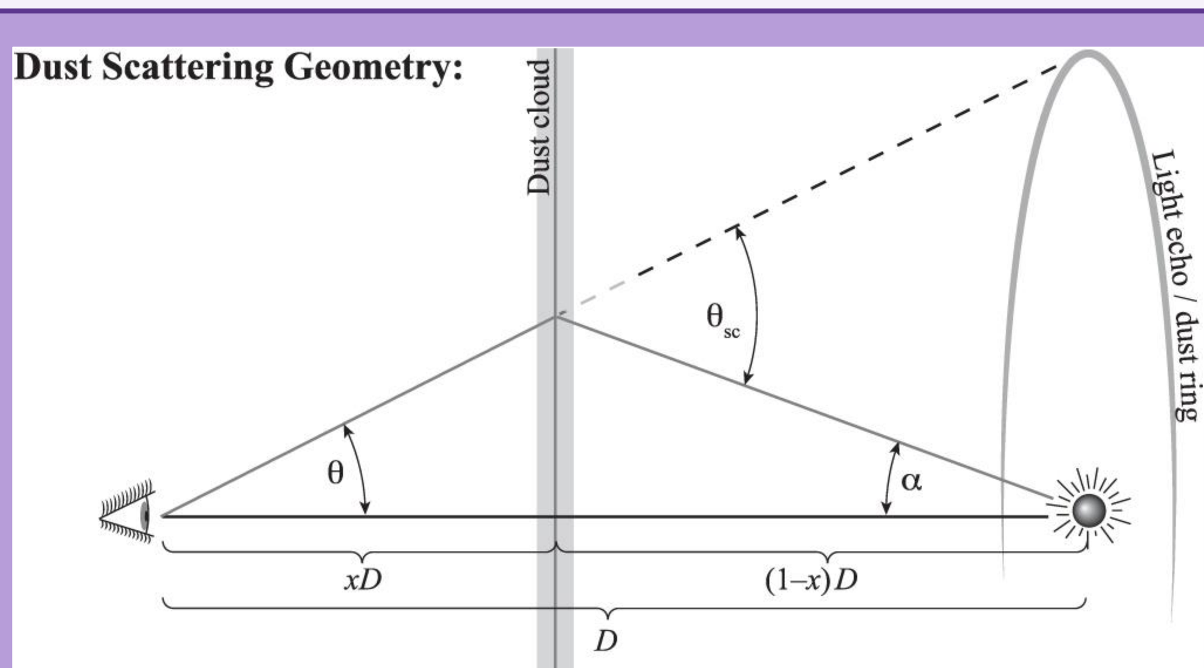

Figure 1: Illustration of light echo geometry from Heinz et al. (2015). X-rays from a source at distance D scatter off a dust layer at distance xD from the observer. Light echo rings with an observed angle θ are produced.

As shown in Figure 1, the additional path length ΔD by which the scattered X-ray photons travel is expressed as (Eq. 1):

$$\Delta D = \frac{xD\theta^2}{2(1-x)} \quad \text{where} \quad \theta = \sqrt{\frac{2c\Delta t(1-x)}{xD}}$$

where θ is the observed angle of the scattered X-rays.

The flux of each ring (Eq. 2) is expressed as a function of the hydrogen column density N_H, the differential dust scattering cross section per hydrogen atom ∂σ/∂Ω, and the fluence F_ν, or the time-integrated flux of the outburst.

$$F = \frac{2\pi c N_H}{x(1-x)D}\frac{\partial\sigma_{sc,\nu}}{\partial\Omega}\mathcal{F}$$

If the source is a gamma-ray burst (GRB), the distance to the source is infinite compared to the distance to the intervening dust columns. We can then simplify (Eq. 3 and Eq. 4):

$$D_{dust} = \frac{2c\Delta t}{\theta^2} \quad \text{and} \quad N_H = \frac{FD_{dust}}{2\pi c\mathcal{F}\frac{\partial\sigma}{\partial\Omega}}$$

Then, if we have an image of the light echo from which we can measure the observed scattering angle, we can **directly calculate the distance to dust columns, only limited by the angular resolution of the telescope.**

Swift Imaging of GRB 221009a

To observe a light echo, a source needs to be both bright and located behind a significant amount of dust ($N_H > 10^{21}$ cm^{-2}). GRB 221009a's high intrinsic luminosity ($L_{iso} \sim 10^{54}$ ergs/s), relatively nearby distance (D_L = 745 Mpc), and proximity to the Galactic plane (b = 4.32°) make it an **ideal source** for X-ray dust tomography.

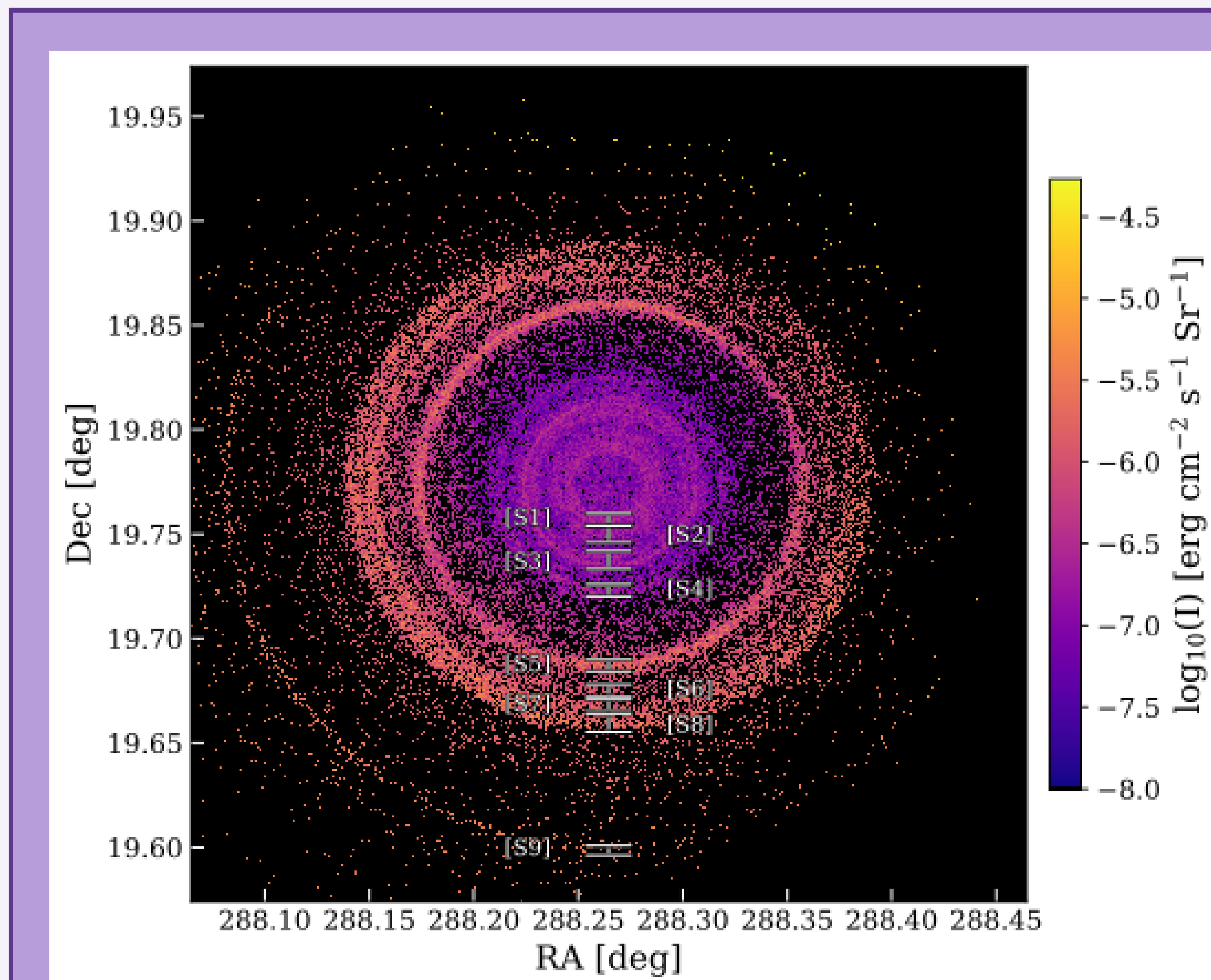

Figure 2. Stacked Swift XRT-PC image of the GRB 221009a light echo, consisting of 35 *Swift* observations. Each was scaled in angular size to the first observation. Rings are labeled [S1]-[S9]. The source position is located in the center of the image.

We combine 35 *Swift* observations of the GRB 221009a light echo, spanning from the day of the outburst to about 32 days afterwards, to capture its evolution over time. By leveraging *Swift*'s ability to preserve each photon's position, timing, and energy, we develop a **new technique** to study the light echo rings on a photon-by-photon basis.

For a photon at an observed angle θ, we map it to a smaller angle that matches the angular size of the first *Swift* observation, thereby returning the rings to their peak position. As shown in Figure 2, we find **9 prominent rings** through visual examination and a radial intensity profile.

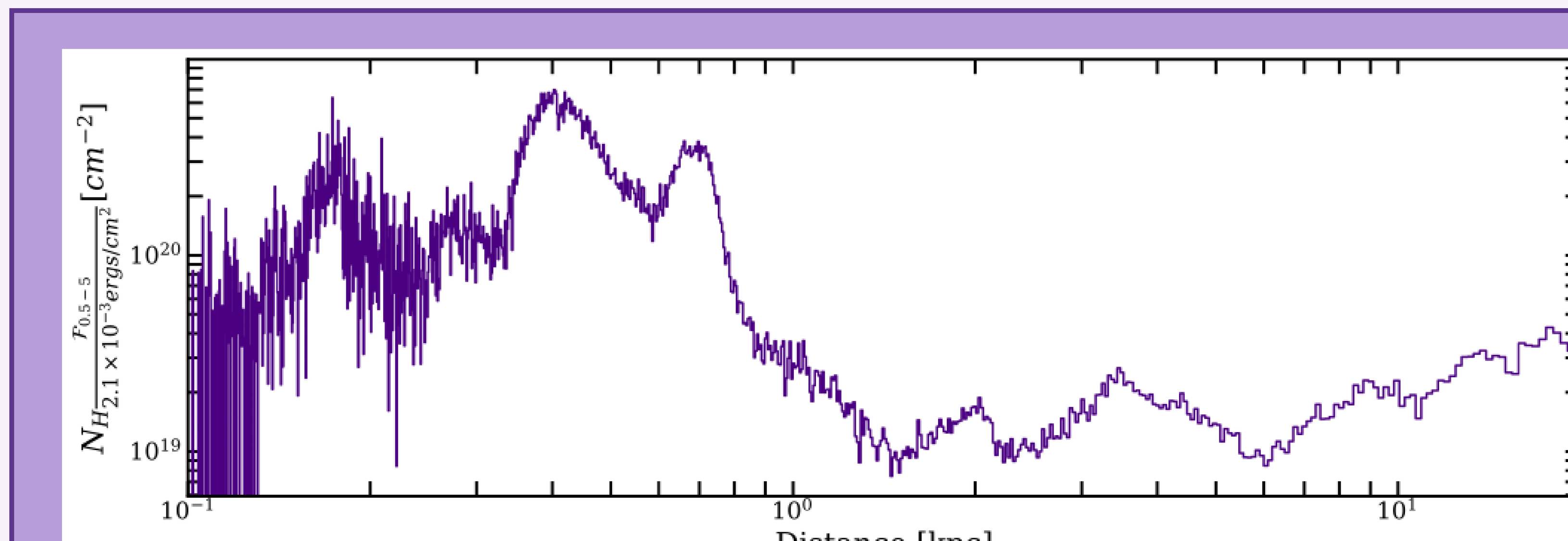

Figure 3: Column density N_H distribution determined using a standard MRN dust model. Dusty structure is visible up to about 18 kpc away.

As shown in Figure 3, we find that these rings correspond to dusty structure **up to 18 kpc away.** The sightline to this GRB then samples an abundance of dust across the Milky Way and high above the Galactic plane. This also demonstrates X-ray dust tomography's sensitivity to concentrations of dust at very far distances.

Comparing with CO

The intervening material along the line-of-sight to GRB 221009a largely exists in the molecular phase. Using CO measurements taken by the IRAM 30-meter telescope, we locate at least **5 components of molecular gas** along the sightline to the GRB, as shown in Figure 4.

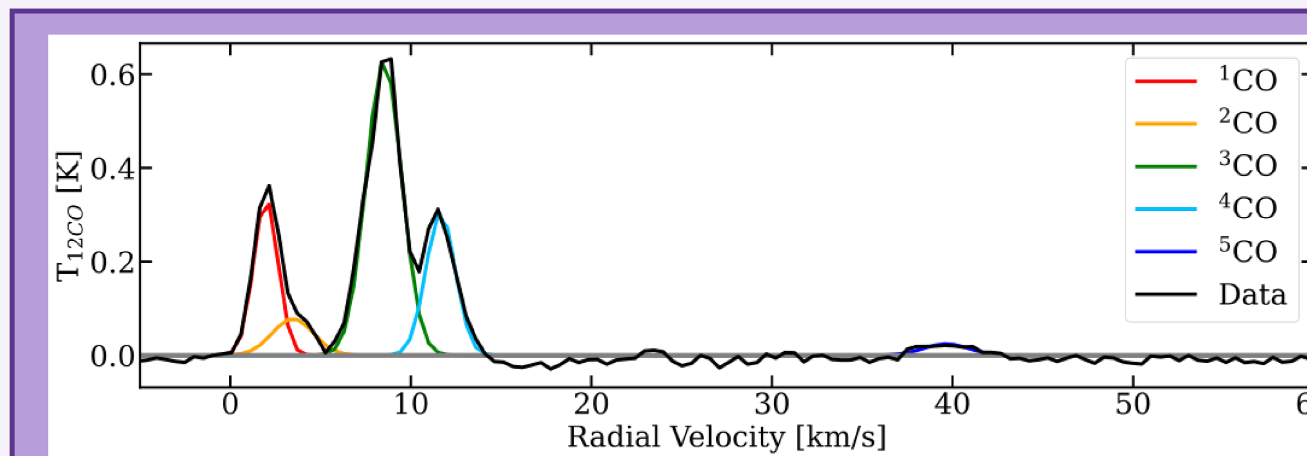

Figure 4. ^{12}CO spectrum averaged across the FOV of the *Swift* observation and the 5 found velocity components $^{1-5}$CO.

We can compare the kinematic distances of these CO clouds with the geometric distances from the *Swift* image to **identify the most probable locations of the dust clouds that produced the light echo**. As shown in Figure 5, we see that for the first 4 components, their near distances coincide with a large amount of column density below 1 kpc. Similarly, for the fifth component, the near distance seems to correspond with dusty structure around 3 - 4 kpc.

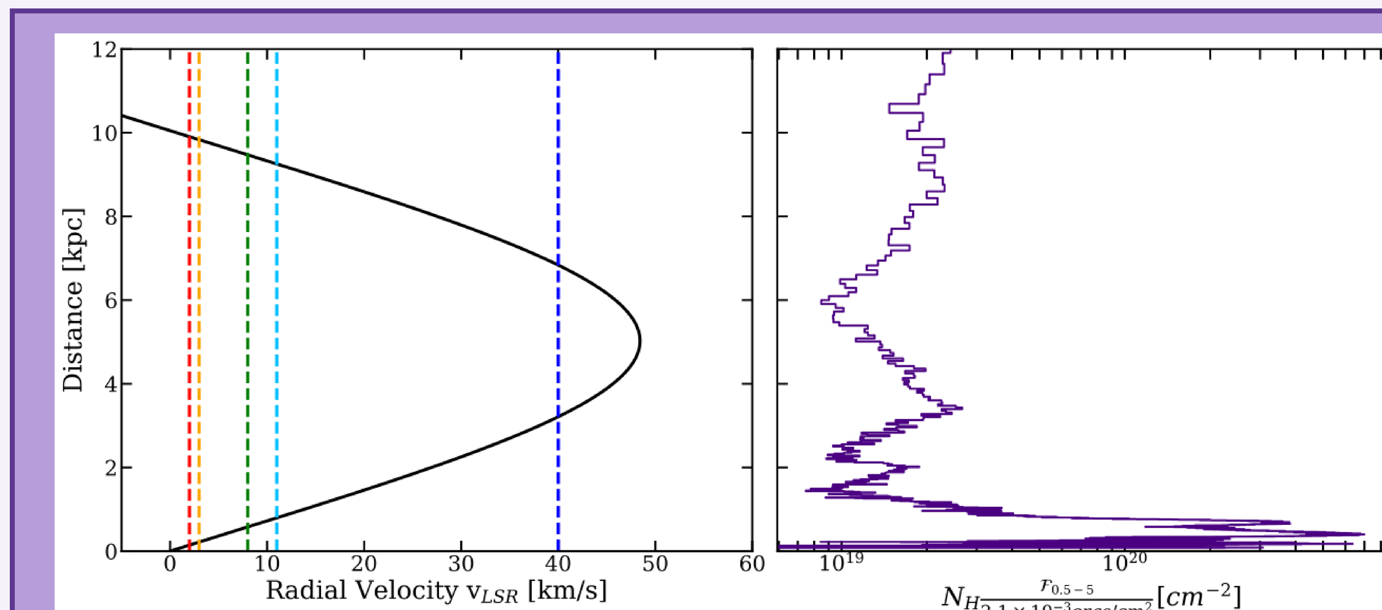

Figure 5. Left: Radial velocity as a function of distance from the Sun using the rotation curve from Reid et al. (2014). Overplotted are the found velocity components. Right: Geometric distances to dust clouds found using the *Swift* image. Dusty structure correlates with the near distances to each component.

However, the kinematic distance to each component of molecular gas is not definitive, as they can spatially overlap. The next steps of this project will involve looking for **deviations from axisymmetry** in the brightness of the echo rings, as this will correspond to variations in the column density of the scattering dust layers. This can be done by comparing the *Swift* image with CO intensity maps and **3D infrared dust maps** to search for any overlaps in regions of high column density, CO emission, and extinction.

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