X-ray Dust Tomography: the New Frontier in Galactic Exploration

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Imagine a dusty basement with bright sunlight streaming through a narrow window: The rays of light will reflect off tiny dust particles floating through the air, creating a silver stream of light. This is dust scattering in action, an illustration of a process happening throughout the universe.

When astronomers discuss dust, they refer to something much less macroscopic than the kind of dust you might wipe up from your window sill or the dust-bunny you find in a hard-to-reach corner under your bed. Astronomical dust is anything bigger than a molecule (a typical dust grain spans anywhere from a few hundredths to a few tens of microns, orders of magnitude smaller than the width of a human hair) and is typically the only kind of solid matter found in interstellar space. Around 90-100% of interstellar silicon, magnesium, and iron—the same materials that comprise the Earth's crust—are locked in solid form.

This is no coincidence: Dust serves as an interstellar transport for these materials. Interstellar dust also plays a vital role in forming new stars—and planets—by shielding molecular gas from destructive ultraviolet light so that it can form the dense, cold, clouds that are the nurseries of stars. Dust grains also serve as a catalyst by providing a surface for chemical reactions on which to form complex molecules and ices in molecular clouds and protostellar disks.

It is probably fair to say that the typical astronomer will have an underdeveloped appreciation for interstellar dust. That's because dust gets in the way of observations at visible and shorter wavelengths and makes life harder for astronomers by absorbing and scattering photons, making images darker and, at X-ray wavelengths, blurrier.

But dust deserves a second look not just because it is a key ingredient in the formation of planets and stars: Dust can also be an important observational tool. For example, infrared astronomers have long used the emission from cool dust grains at long wavelengths to search for concentrations of dense gas that are invisible at other wavelengths to find heavily obscured black holes in the centers of distant galaxies.

Much of our knowledge of interstellar dust is indirectly inferred from meteoritic materials, extinction curves spanning the infrared to ultraviolet, comparisons of gas phase metal line absorption to solar abundance (depletion), and some infrared absorption and emission lines, many of which come from unidentified molecular species (Draine 2003b). X-ray light can provide crucial insight into many outstanding dust questions through the phenomenon of absorption and scattering.

The prospect of scattering of X-rays by interstellar dust (Overbeck 1965) was realized almost immediately following the discovery of the first X-ray point sources outside of the solar system (Giacconi 1962) and has been a mainstay of studies of interstellar gas ever since. Surveys of X-ray scattering halos have been used to measure relationships between optical extinction, gas column, and distance (Predehl & Schmitt 1995, Valencic & Smith 2015).

With the launch of the current generation of flagship X-ray imaging telescopes, *Chandra*, *XMM-Newton*, and *Swift*, a new diagnostic has become available to X-ray astronomers: High-resolution dust tomography from X-ray scattering studies, that is, the use of dust scattering echoes to measure distances, to map the distribution of matter throughout the galaxy, and to determine the properties of interstellar dust grains.

Dust Echoes and Halos Explained

X-ray scattering has long been used as a laboratory tool to study the structure of solid matter through Bragg-crystallography. Like solid matter in the lab, interstellar dust grains can scatter X-ray photons. They can also absorb X-rays, and whether a photon is absorbed or scattered by a dust grain (or whether it just flies by unaffected) is set by the dust scattering cross section—the probability of a photon being scattered in a particular direction by a dust grain—which depends very strongly on the angle at which the photon interacts with the dust grain and the outgoing angle of the scattered photon.

Scattering is restricted to very small angles, a degree or smaller, and all X-ray dust scattering is forward-scattering. Dust scattering cross sections are so small that typically only a few percent of the X-ray light gets scattered. In order to see meaningful surface brightness from scattering, one needs both a bright X-ray source and significant amount of dust between the observer and the source.

At any given time the Galaxy is illuminated by dozens of bright point sources, all powered by compact objects: Neutron stars and black holes. These sources

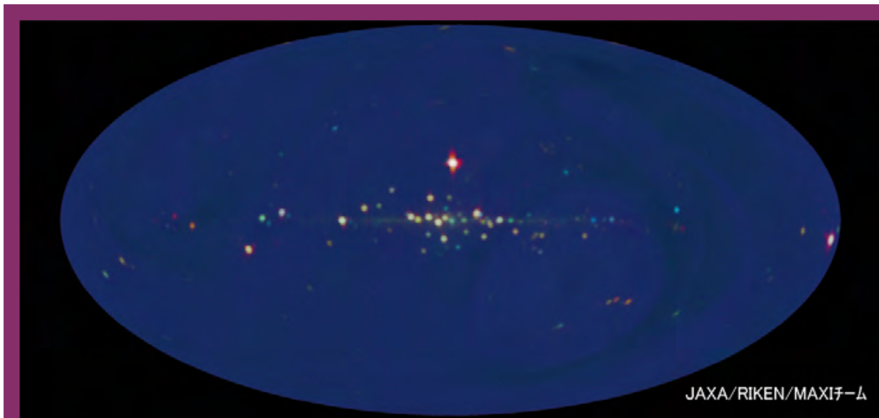

Figure 1: X-ray image of the entire sky from several years of observation, taken by the MAXI instrument aboard the International Space Station (Matsuoka et al. 2009), showing dozens of sources in the plane of the Milky Way.

make excellent beacons around which we can study the interaction of X-ray light with interstellar dust. Figure 1 shows an image of the X-ray sky, taken by the MAXI instrument onboard the International Space Station, dotted with bright point sources.

Most bright X-ray sources lie in the plane of the Milky Way, which is good news for the study of dust because most of the Galaxy's dust is found right along that plane. How, then, does interstellar dust interact with the X-rays emanating from a distant source, and what do we see with *Chandra* as a result? Observationally, we can categorize the signal into three groups, based on the appearance and information content that can be extracted:

Constant dust scattering halos are formed by persistently bright X-ray sources behind a thick veil of dust. These fuzzy hazes of X-ray light were first discovered by the Einstein X-ray Telescope (Rolf 1983) and have been studied for decades. They are the easiest to observe—just point your X-ray telescope at a bright X-ray point source in the plane of the Galaxy—but hardest to extract information from because the interplay between scattering angle and dust location is hard to disentangle.

Variable dust scattering halos are formed by bright, but variable X-ray sources behind a thick veil of dust.

X-ray ring echoes are, in a sense, the jackpot of echo studies: they are rare and hard to observe—only three bright, large ring echoes have been observed to date—but they offer the cleanest, most detailed and easily interpreted signal.

This article will focus on the last two relatively new avenues of dust study, where *Chandra* can truly shine: variable scattering halos and ring echoes.

The front cover of this newsletter shows the 2014 echo from the neutron star Circinus X-1, with four colorful rings, centered on the source. To understand why we see multiple rings and what kind of information is encoded in images like this, it is instructive to go through the signal step by step, illustrated by the cartoon in Figure 2.

Suppose a neutron star emits a flash of X-rays. Without any dust between us and the neutron star, all we would see is a single flash of X-rays from the position of the source.

How does dust alter the signal? Dust grains can scatter some of the X-ray photons initially emitted by the neutron star in (slightly) different directions towards our telescope. We will see these scattered X-rays arriving from a different direction in the sky with a time delay compared to the flash of X-rays arriving directly from the black hole. Because of the change in direction, the path the scattered photons take is longer than the direct path from the source—typically a few days.

X-rays arriving at the telescope some time after the initial flash must have been scattered on the surface of an ellipsoid, with the telescope and the X-ray source at the two focal points. That is because an ellipsoid is the surface of constant path length between the two focal points and any point on the surface, so any photon scattered on the surface of that ellipsoid will have traveled the same distance to the observer. The longer the time delay (the later the observation) the larger the ellipsoid. Because of the large distance involved and the small angles that scattering is restricted to, dust scattering ellipsoids are extremely long—about a thousand times longer than they are wide, so the scattering ellipsoid in the cartoon is not to scale.

While dust can be found throughout interstellar space, the largest concentrations along any given direction are located inside dense, cold, molecular clouds. We will see scattered photons mostly from the intersection of the scattering ellipsoid and the dust clouds—each forming a ring in space that will appear as a ring on the sky. The longer the delay (the later the image is taken), the larger the ellipsoid and the larger the ring.

Each cloud between us and the source intersects the scattering ellipsoid at a different place and creates its

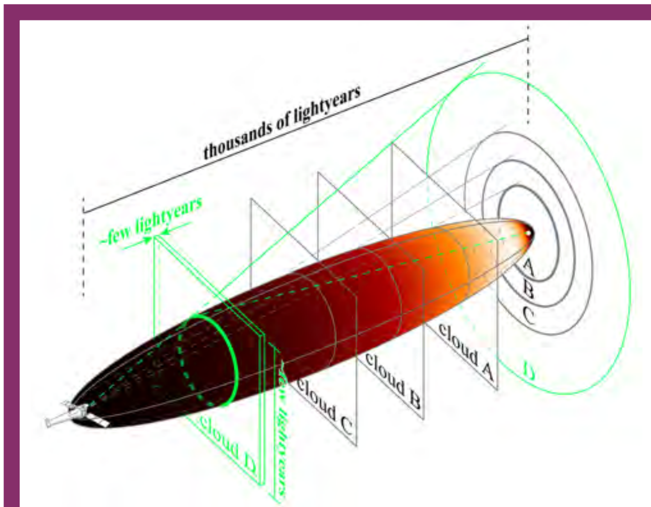

Figure 2: An illustration of dust scattering: The echo of a an X-ray flare from an X-ray source (white dot) is produced on the surface of an ellipsoid (shaded surface). We see rings from the locations where dust clouds between Earth and the source intersect the ellipsoid. Each cloud produces a different ring. The echo is brightest where the shade of the ellipsoid is lightest. The illustration is not to scale: In reality, the ellipsoid is highly elongate: thousands of lightyears long and only a few lightyears across. In this example, the green cloud and light path demonstrate the generation of the outermost ring.

own echo ring; the closer the cloud, the larger the ring will appear in the sky. By measuring the size of the ring and the time delay, we can measure the relative positions of the clouds between us and the source.

The brightness of the rings depends on where on the scattering ellipsoid they are created—there is a sweet spot with maximum brightness per amount of dust. Rings from clouds that are closer or farther than that spot are progressively dimmer.

If the flare lasts for a longer time, a few days or even weeks, the rings become thicker. The longer the flare, the thicker the rings appear on the sky. This explains the difference between ring echoes and dust scattering halos: If the source is not flaring at all but shining continuously, like many Galactic X-ray sources, there is no ring—the entire cloud is illuminated—and we see a diffuse glow that we call a dust scattering halo. Each cloud produces such a halo, making for one fuzzy glow, so we can no longer simply read off the relative position of the dust from the image, making interpretation much harder.

Ring echoes

While ring echoes are the most powerful probes in the arsenal of dust scattering studies, they are also hardest to observe:

They require short, bright flares of the source followed by quick dimming, so that the echo is bright and the source does not continue to generate a bright dust scattering halo competing with the rings.

They require a lot of dust between us and the source—only sources in the plane of the Milky Way can produce ring echoes. To put the amount of dust needed into perspective: If we were to compress the amount of gas and dust between us and the source into a sheet of paper, it would have the thickness of cardstock.

They must be observed quickly after the flare—the rings grow in size and fade rapidly, making them unobservable after just a few weeks. Because flares are unpredictable, the observations of rings must be scheduled quickly and on the fly. Such scheduling is hard for most X-ray telescopes, including *Chandra*.

The right kind of flares are rare, and they have to be in an observable part of the sky.

To date, only three bright ring echoes have been observed. However, with every echo we learn how to better schedule telescopes to catch echoes and to analyze the data in new ways, and over the coming decade, echo tomography will become a standard tool in X-ray astronomy.

1E 1547.0-5408:

Figure 3 shows an image of the first X-ray ring echo from a Galactic source, the X-ray pulsar 1E 1547.0–5408 that flared in 2009 (Tiengo et al. 2010). It was observed by the *Swift* and *XMM-Newton* telescopes and showed three rings expanding with time.

What can we learn from this echo? The most obvious thing is the location of the dust, in relation to the location of the pulsar, to better than 1% accuracy. Dust clouds are expected to be found preferentially in or near spiral arms, so determining the location of clouds is a way to map the spiral structure of our Galaxy. Something that would take a space-ship and a long trip towards the Andromeda Galaxy to do—making an image of our Galaxy in dust—can be accomplished with a few X-ray observations. Figure 6 overlays the location of the dust clouds towards 1E1547.0-5408 inferred from the echo on the map of the Milky Way.

Better yet, the cloud map we can construct from the echo in a given direction is 3-dimensional: two image dimensions (left-right and up-down relative to the plane of the Galaxy) and one time dimension (delay since the flare) that we can translate into a measurement of depth. This makes X-ray dust studies similar to an MRI machine taking images of the Galaxy's skeletal structure.

Circinus X-1:

A light echo itself only measures the relative distance to the source: a given cloud may be at, say, half the distance to the source. To put that dust on the Galactic map, we need to know the distance to the source from some other means.

Trümper & Schönfelder (1973) first proposed to use the echoes themselves to determine the distance, much like bats use echolocation to measure distances. For dust echoes to do this, they must be combined with one more diagnostic. This is best illustrated using the brightest, largest echo observed to date: the 2014 echo from the neutron star Circinus X-1 (Heinz et al. 2015).

In late 2013, Circinus X-1 illuminated the X-ray sky with an enormous flare that lasted two months and made it one of the brightest X-ray sources in the Galaxy. Then it abruptly dimmed. Perfect conditions for this heavily obscured source right in the plane of the Milky Way to exhibit a ring echo. The *Chandra* image in Figure 4 shows a series of four wide rings, centered on the neutron star.

The rings allow a detailed reconstruction of the dust distribution between us and the source, showing the presence of at least for dust clouds. The rings are much wider than those of 1E 1547.0-5408 because the flare lasted for almost two months.

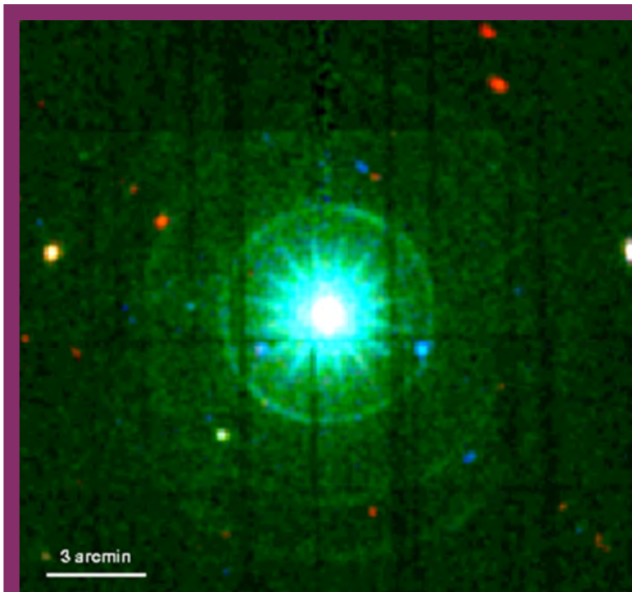

Figure 3: XMM-Newton image of the first ring echo from a Galactic source, the anomalous X-ray pulsar 1E1547.0-5408, showing three rings (Tiengo et al. 2010).

Figure 4: Chandra image of the 2014 ring echo of the neutron star Circinus X-1. The image shows four colorful rings, centered on the neutron star (blue) and the supernova remnant (red glow). The variation in brightness and color within each ring allows identification with individual molecular clouds found in Carbon Monoxide emission.

Like in the case of 1E1547.0-5408, the distance to the Circinus X-1 was not known before the observation, with estimates ranging from 12,000 to 45,000 lightyears. But unlike in the case of 1E1547.0-5408, the rings of the Cir X-1 echo are not uniformly bright. Each ring has clear bright spots and dark regions. For a ring to be bright in a particular place requires an extra amount of dust in the cloud in that direction. By measuring the brightness of each ring, we can map the distribution of dust within each cloud.

That distribution is different for the different clouds. And because we know that dust clouds are associated with clouds of cold, molecular gas, we can search observations of that gas at other wavelengths for the same fingerprint pattern.

In the case of Cir X-1, this can be done with observations of the Galaxy in Carbon-Monoxide (CO), a common molecule and the most sensitive tracer of cold gas. The entire Southern half of the plane of the Milky Way has been mapped in CO by the Australian Mopra radio telescope (Burton et al. 2013). Each cloud of cold gas and dust along a given direction can be found in the CO data. If the dust cloud responsible for a given ring is densest in a particular point in the sky, the corresponding cloud in CO should be bright

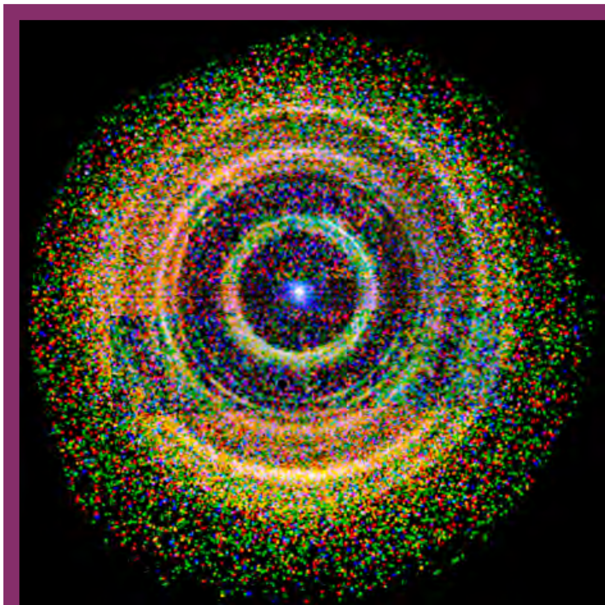

Figure 5: Combined Chandra and Swift image of the 2015 light echo from V404 Cygni, showing a record-setting eight rings. The distance of 7.2 light-years to the black hole visible in the center of the image is known very precisely, allowing accurate measurement of the distances to the eight clouds responsible for the rings.

in that spot as well. We can match the dust and CO brightness patterns like fingerprints to identify clouds.

From the Doppler shift of the CO emission line and the law of Galactic rotation, we can measure the distances to both the clouds and the neutron star at the same time. The implication is that Circinus X-1 lies at a distance of about 27,000 light-years—narrowing the uncertainty in the distance to the source from roughly a factor of three to about 15%. After the prediction 43 years ago, X-ray astronomy is now able to measure echolocation distances.

V404 Cygni:

Echoes can put dust clouds on the Galactic map, but an equally important question is: what kind of dust are they actually made of? If we have a sufficiently detailed set of measurements, the echo can measure the properties of the dust grains themselves—their composition and sizes. That is because different size dust grains reflect different X-ray energies in preferentially different directions, and different dust mineralogy also leads to different reflectivity at different angles.

In June 2015, the Galactic black hole X-ray binary V404 Cygni went into an extreme outburst, after spending 26 years in quiescence. For a few days it became the brightest source in the X-ray sky, flickering rapidly and then shutting off as quickly as it had gone into outburst (Barthelmy, D'Ai & D'Avanzo 2015, Rodriguez et al. 2015).

The source is located in the plane of the Galaxy, behind a layer of dust thick enough to generate the bright echo found by Beardmore et. al. (2015). They found four expanding and fading rings, setting off a month-long observing campaign.

Both *Swift* and *Chandra* observed the echo, making a perfect tag-team. *Swift* is designed to look rapidly at bright sources, so flexibility is built into the way the mission operates, making it ideal to catch echoes quickly. *Chandra*, on the other hand, has much higher imaging resolution and is more sensitive—making it ideally suited to look at the echo with optimal image fidelity—but harder to re-schedule quickly to look at the echo early on. *Swift* observed the echo early and often, for short snapshots, while *Chandra* spent time looking at the late echo to extract the information at the highest possible resolution.

By combining all observations from *Swift* and *Chandra* in Figure 5, we can reconstruct a detailed image of the entire echo, revealing a record-setting eight rings.

The distance to V404 Cyg—7200 lightyears—is known independently from the echo from previous radio observations (Miller-Jones et al. 2009). The echo therefore measures the distances and sizes of the dust clouds (shown in Figure 6) with almost pinpoint accuracy.

With accurately known distance, the echo can probe the details of dust physics in exacting detail (Vasilopoulos & Petropoulou 2016,Heinz et. al. 2016). To measure a small signal, we need both accuracy and leverage. The leverage in this case comes from the long series of observations—over 52 in all, following the evolution of the rings in brightness and size.

Fitting the extensive data set with different dust models (Mathis, Rumpl, & Nordsieck 1977, Weingartner & Draine 2001, Zubko et al. 2004) shows that the dust is not the same from cloud to cloud: The two clouds closest to V404 Cyg seem to have a significant excess of small dust grains compared to the remaining clouds. Grains are destroyed by shock waves, UV light, and cosmic rays, and the relative lack of large grains in a cloud tells us that the dust in the clouds closest to V404 Cyg was likely processed by a shock, breaking up the large grains to make more small grains.

The dust between us and V404 Cyg is chemically simple—graphite and silicate grains are all that is needed to explain the echo. Complicated grains with ice mantles or mixed chemistry do not fit the data.

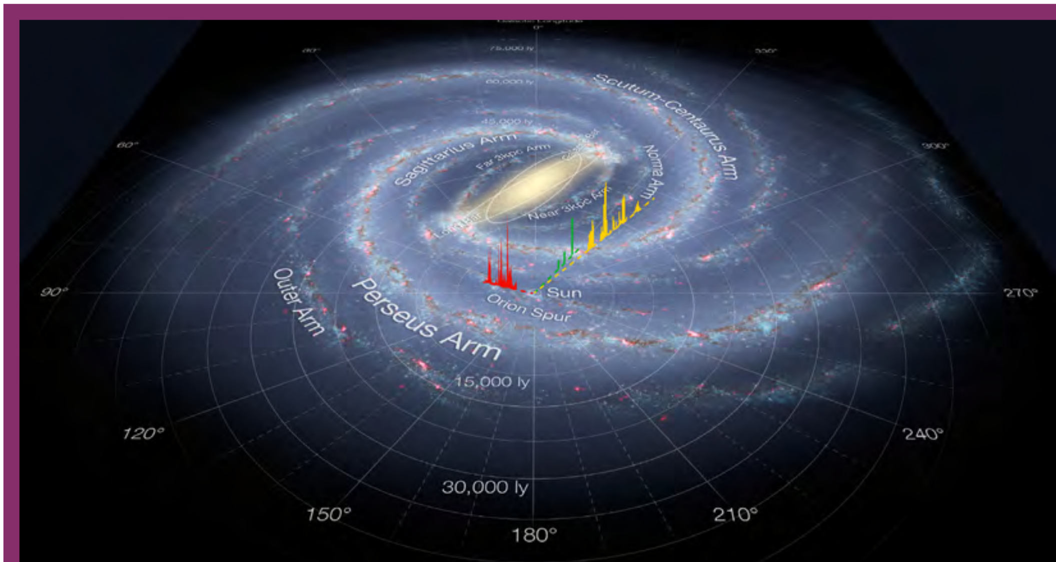

Figure 6: The dust distributions towards V404 Cygni (red; Heinz et al. 2016), Circinus X-1 (yellow; Heinz et al. 2015), and 1E1547.0-54.08 (green, from Tiengo et al. 2010, assuming distance of 3.9 kpc) derived from the dust echoes, overlaid on an artist's impression of the Milky Way Galaxy (NASA/JPL-Caltech/ESO/R. Hurt). With more data from future echoes, the gaps in coverage to these sources will be filled in. Echoes from other sources will begin filling in the missing sight- lines in the still very sparse image.

Dust echoes are therefore able to chemically type different Galactic dust environments.

The Unique Sightline of Cygnus X-3

Variable scattering halos provide a similar form of diagnostic: When a source with a halo changes brightness, the echo from the change will ripple through the halo. By comparing the change in the halo to the brightness variations of the source, it is possible to constrain the location and scattering properties of the dust (Xiang et al. 2011).

Cyg X-3 is a high mass X-ray binary with one of the brightest scattering halos visible. In its quenched state, Cyg X-3's light curve exhibits steady sinusoidal variations with a period of 4.8 hours. Just 10 arcseconds away, a small X-ray feature imaged by *Chandra* (dubbed Cyg X-3's "Little Friend"; McCollough et al. 2012) also varies in brightness with the same period, but shifted in phase. This is the most distant "Bok globule" ever found—a tiny cloud containing a few solar masses of gas and dust confined to sub-parsec scales—discovered via X-ray scattering!

About 30,000 light-years away, the foreground of Cyg X-3 is host to many interesting environments. In addition to the Little Friend, there is the Perseus arm of the Milky Way and the stellar association Cygnus OB2, which is embedded in the larger Cygnus X star forming region. Cyg X-3 is thereby uniquely positioned as a laboratory for studying different phases of the interstellar medium, the dust growth that occurs in molecular clouds, and dust composition.

Combining the known properties of the sightline towards Cyg X-3 with detailed spectral analysis of the scattering halo, Corrales & Paerels (2015) found evidence that the scattering halo brightness falls significantly below the brightness expected for typical Milky Way dust grain populations. One explanation is that the Cyg OB2 association contains grains that are much larger, by a factor of 5-10, than the typical upper limit for grain sizes in the diffuse interstellar medium.

Frontiers of Dust Scattering

In early 2016, with three ring echoes in the archives, each spanning about a half degree across the sky, we are beginning to see the dusty galaxy in high-definition, leaving about 358 Milky Way degrees more to go. With some luck and a lot of hard work, *Chandra* will stay busy over the coming decade.

Alongside new observations, a new suite of models is being developed to study the spectra of echoes and halos in much more detail. The potential to measure details in the molecular structure (Smith et al. 2016, Heinz et al 2016, Corrales et al. 2016) and perhaps even the shapes of dust grains (Hoffman 2016) promise a rich field of study.

And with the launch of the next generation of ultra-sensitive X-ray telescopes—*Athena* and *X-ray Surveyor*—the study of echoes will become orders of magnitude more powerful, allowing the study of echoes up to 100 times fainter than the few cases observed so far, opening up a vast population of potential echoes from both dimmer sources and sources with lower amounts of dust to scatter X-rays.

As the light collecting power of X-ray instruments increases with future missions, we increase our prospects for studying not just echoes from within the Milky Way, but even extragalactic dust with X-ray scattering, with the potential to measure distances to

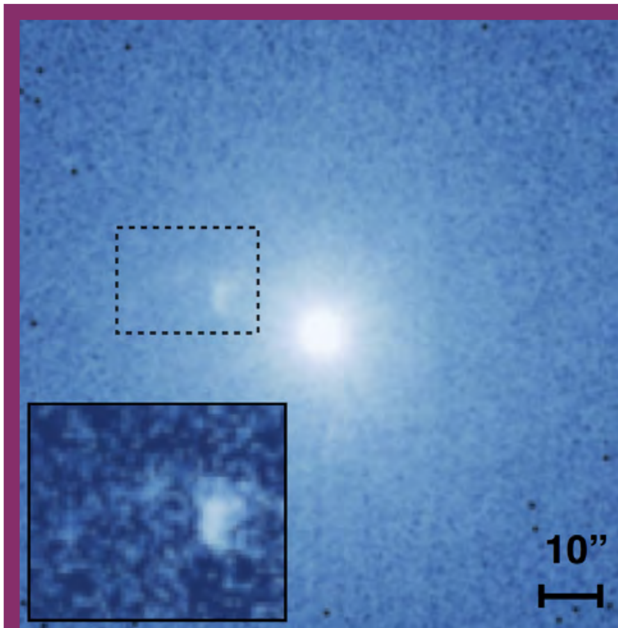

Figure 7: The high mass X-ray binary Cygnus X-3 has one of the brightest dust scattering halos in the sky. In this 50 ks high resolution image from Chandra, a small knot of X-ray brightness can be seen 16” from the central source. This is Cygnus X-3’s “Little Friend”, a dense cloud of molecular gas about 0.2 pc in size. The inset shows hints of additional structure around the Little Friend, obtained after subtracting the mean count rates from the smooth dust scattering halo.

nearby galaxies (Draine & Bond 2004). Given our understanding of the star formation history over cosmic time, current estimates indicate dust in galaxy disks accounts for as little as one third of the overall dust produced in the Universe (Ménard & Fukugita 2012).

Dust can be seen several kpc above the disk of M82, the famous star bursting galaxy whose outflows shine in both the infrared and X-ray. Additionally, cross-correlations between quasar-galaxy and galaxy-galaxy pairs show evidence of reddening at optical wavelengths—a tell-tale sign of dust—in the circumgalactic medium (Ménard et al. 2010, Peek et al. 2015). Since many quasars also shine brightly in the X-ray, this invites the possibility of searching for X-ray scattering from dust in foreground galaxies or the diffuse intergalactic medium.

Only a few percent of a quasar’s light would be scattered by extragalactic dust on the path to Earth. We are more likely to find extragalactic dust if a bright quasar suddenly turned off. Much like the Galactic black holes and microquasars we see today, accretion onto the supermassive black holes powering a quasar can be subject to intense fluctuations. These accreting giants could leave behind a dust scattering echo—visible as a solitary ring of X-ray brightness, or “ghost halo”—tens to hundreds of years after the black hole is done eating. With *Chandra*, our sensitivity is mainly limited by the instrument background, and we might only catch one echo over the entire sky (Corrales 2015). The proposed *X-ray Surveyor* mission will have 30 times the collecting area of *Chandra* with the same resolution, making it the ideal laboratory for detecting ghost halos from the high-z Universe. ■

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