AstroTalk: Behind the news headlines of May 2017

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Planetary formation is disks of dust and gas unveiled

Newborn stars are typically located in disks of gas and dust. When planets first begin to form, rings of rocky and icy material ('planetesimals') form. The dust in those rings starts to stick together, growing until clumps develop that are large enough to attract other clumps because of their gravity. Astronomers believe that the process of forming planets and dissipating the disk takes about 10 million years. Many mysteries remain, however, including the tendency of dust not to stick together, and the likelihood that colliding clumps could break apart rather than agglomerate.

As analogues to our own Solar System's 'Kuiper Belt' or 'Oort Cloud,' the disks of debris left over from planet formation can be detected by astronomers and studied to help understand the processes that create planetary systems. Astronomers recently presented new observations of a nearby planetary system known as '61 Virginis' ('61 Vir') and its debris disk. 61 Vir is a 4.6-billion-year-old star, about the size of our Sun, which is located approximately 28 light-years away. At least three planets orbit the parent star, which are five, 18, and 23 times more massive than the Earth. One of the most intriguing features of this system is its debris disk, which extends from 30 to at least 100 astronomical units ('au,' the average distance from the Sun to the Earth) from the star.

A team of astronomers led by Sebastian Marino of the University of Cambridge (UK) has performed observations of 61 Vir's debris disk using the Atacama Large Millimetre/submillimetre Array (ALMA) in Chile. These observations were complemented by data from the Submillimetre Common-User Bolometer Array 2 (SCUBA2) installed at the James Clerk Maxwell Telescope (JCMT) at Mauna Kea Observatory, Hawaii.

> "*In this paper, we present the first observations of 61 Vir with ALMA at a wavelength of 0.86 mm, obtained with the aim of studying its debris disk to reveal the location of the parent planetesimals, and place constraints on the presence of planets at large separations that can shape the mass distribution in the disk. … In order to obtain the best disk constraints, in our analysis we combine new ALMA observations and new data at 0.85 mm from SCUBA2 installed on JCMT, thus, incorporating information from small and large angular scale structure*," the researchers wrote.

The new study reveals that the 61 Vir debris disk is larger than previously thought. Marino's team found that it extends from 30 au to at least 150 au. Moreover, the researchers assume that an as-yet unseen fourth planet may lurk somewhere in the system, between 61 Vir d at 0.5 au and the inner edge of the disk. They argue that if the disk was stirred at 150 au by an additional planet, that unseen alien world should have a mass of at least 10 Earth masses and it should orbit its host at a distance between 10 and 20 au.

> "*We found that in order to have stirred the disk out to 150 au, the planet must be more massive than 10 Earth masses and a semi-major axis between 10 and 20 au. [For other reasonable assumptions about its orbit,] it could have a lower mass and a semi-major axis between 4 and 20 au*," the team concluded.

Indeed, determining how the gravity of existing planets influences a disk's architecture is another important area of study. Most of this research focuses on how planets that exist inside the debris disk define its shape, which is one of the few disk characteristics that can be observed directly from Earth. The Carnegie Institution's Erika Nesvold recently explored how a disk is affected by a planet that exists beyond its outermost edge, demonstrating that the disk's shape can indicate whether the planet formed beyond the disk or if it initially existed inside the disk and moved outwards over time.

The star HD 106906 is perfect for studying this phenomenon. It has one giant planet, about 11 times the mass of Jupiter, orbiting very far away from its host star, at at least 650 au. This planet, HD 107906b, orbits outside of its star's debris disk, which is about ten times closer to the star than the planet.

Nesvold and her colleagues modelled the HD 106906 system to better understand how an outside planet affects the structure of a debris disk.

> "*We were able to create the known shape of HD 106906's debris disk without adding another planet into the system, as some had suggested was necessary to achieve the observed architecture*," Nesvold said.

The single, distant giant planet's gravity was able to affect the debris in just the right way to produce the system's flat, non-circular ring and to account for the disk's observed shape and features. In addition, Nesvold's model was able to help her and her team better understand the orbit and likely formation history of the planet HD 106906b. The team's results indicate that it's likely that the planet formed outside the disk. If the planet had formed inside the disk and moved outwards, the disk would have taken on a different shape than the one shown by the observations.

> "*Other debris disks that are shaped by the influence of distant giant planets are probably likely*," Nesvold added. "*My modelling tool can help recreate and visualize how the various features of these disks came to be and improve our understanding of planetary system evolution overall*."

Detailed explorations of exoplanets have recently begun to overlap with studies of planetesimal disks, enabling astronomers to probe the development and evolution of a star's system of planets and their interactions with the disk.

Direct imaging of dust disks has been very limited, and so far has principally probed regions in disks at the outer zones of planetary systems. At the same time, the vast majority of exoplanets discovered and studied so far have been very close to their own stars, even within a distance that, if they were located in our own Solar System, would place them within the orbit of Mercury, the planets closest to our Sun.

Direct imaging of the star HR8799 has revealed the presence of multiple planets. Its circumstellar disk has been known to exist for several decades, and has been modelled as having three zones: an inner asteroid-belt analogue, a planetesimal belt from about 100 au to about 430 au, and a halo region extending out to over 1500 au. Harvard-Smithsonian Center for Astrophysics (CfA) astronomer Denis Barkats and a team of colleagues used the ALMA submillimetre array to image the disk around HR8799 with a spatial scale as small as only 32 au, enough to probe the inner zones of the disk. The team determined that the inner edge of the planetesimal belt actually starts at around 145 au, and that the belt extends out to 430 au.

The known four exoplanets in this system orbit inside this inner edge. The most distant of the four planets, planet 'b,' has a chaotic orbit that is expected to take it beyond this inner edge, which therefore poses a stability problem in this interpretation. The astronomers propose two interesting suggestions: either that the orbit of planet 'b' has varied over time more than thought, or that there is a fifth, so-far undetected small planet in a larger orbit whose gravity provides some stability.

The research field of debris-disk direct imaging is 'hot' at the present time, with ALMA observations taking the lion's share of the credit for these developments. By examining the atomic carbon line from two young star systems—49 Ceti and β (beta) Pictoris—Japanese researchers recently found atomic carbon in their disks, the first time this kind of observation has been achieved at submillimetre wavelengths, hinting that the gas in debris disks is not primordial, but rather may have been generated by some process of collisions taking place in the debris disk. Radio observations had detected gas within a number of debris disks, but it was not clear why the gas was there. There are two major hypotheses: either the gas is primordial gas from the original gas cloud that formed the star, or it originates from collisions between objects in the disk.

In search of a solution to this problem, a team from the RIKEN Star and Planet Formation Laboratory decided to look at carbon emission, which is important, since it can provide clues as to the origin of the gas. Normally, carbon will exist mostly in molecular form, as carbon monoxide or 'CO.' Ultraviolet light from the central star will 'dissociate' the atoms, creating free atomic carbon, but normally a chemical reaction—mediated by hydrogen—recombines the carbon into CO. However, if there is no hydrogen, then the reaction does not take place and the carbon remains in its atomic state.

Aya Higuchi was able to use the 10-metre Atacama Submillimeter Telescope Experiment (ASTE) in Chile to examine the atomic carbon emission lines from 49

Ceti and β Pictoris, both known to have debris disks. She and her team then compared this from data on CO taken by the ALMA submillimeter array.

> "*We were surprised*," she says, "*to find atomic carbon in the disk, the first time this observation has been made at submillimetre wavelengths. But more so, we were surprised at how much there was. It was about as common as the carbon monoxide*."

The implication, at least for these two star systems, is that there is very little hydrogen to drive the carbon back into CO. Because hydrogen makes up most of the gas in protoplanetary clouds—the gas clouds from which stars and their planetary systems are thought to form—this suggests that the gas is not primordial, but rather is the product of some process taking place in the debris disk. Gas has been found in other debris disks, but it is not found in all.

> Higuchi says, "*If we can perform similar measurements on other young stars, it will help to clarify the origin of the gas in debris disk. Our data here suggests that the gas is secondary*."

Looking to the future, she continues,

> "*This work will also help to understand how a protoplanetary disk evolves into a debris disks by distinguishing the origin of the gas in the disks*."

Older stars, particularly those older than about five million years, lack evidence of such debris disks, however, suggesting that by this age most of the disk material may have been converted into planets or smaller bodies, accreted onto the star, or dispersed from the system. So-called 'transition disks' bridge this period in disk evolution. They have not yet been disbursed and, warmed by the star, can be detected at infrared or millimetre wavelengths. Their infrared radiation can be used to characterize their properties. They often show inner dust cavities—that is, dust-less gaps inside the disks—which astronomers have sometimes interpreted as evidence of the presence of planets that have cleared out their orbits.

The models of planet–disk interactions, however, indicate that dust cavities are only an indirect consequence of planet clearing. What actually seems to occur is that a planet creates a gap in the gas, and the gas distribution at its outer edges then traps the small dust grains and produces a dust ring that is frequently asymmetric.

Another CfA astronomer, Sean Andrews, and his colleagues used the ALMA submillimetre array to study transition disks in four relatively nearby young stars. This powerful facility can measure dimensions in these disks as small as 24 au, and it can do so for both the small dust grains and the warm gas. In all four disks the scientists were able to model the gas distribution. They found that the gas cavity was as much as three times smaller than the dust cavity, and that the gas density inside the cavity drops by at least a factor of one thousand compared with the surface density. The results strongly suggest that the cavities were indeed produced by orbiting planets.

Many questions remain in this field, and new results appear on monthly timescales. This is indeed an exciting time, particularly now that the ALMA submillimetre array has begun to produce its high-quality data yet.

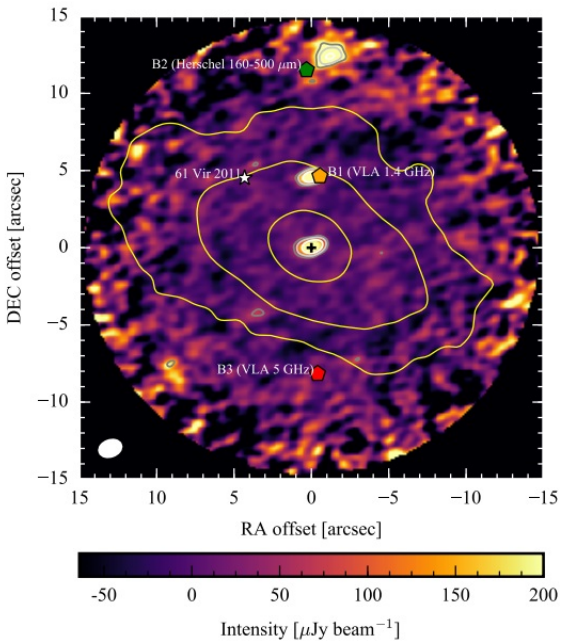

Figure 1: ALMA 0.86 mm continuum image of 61 Vir. (*Credit: Marino et al. 2017*)

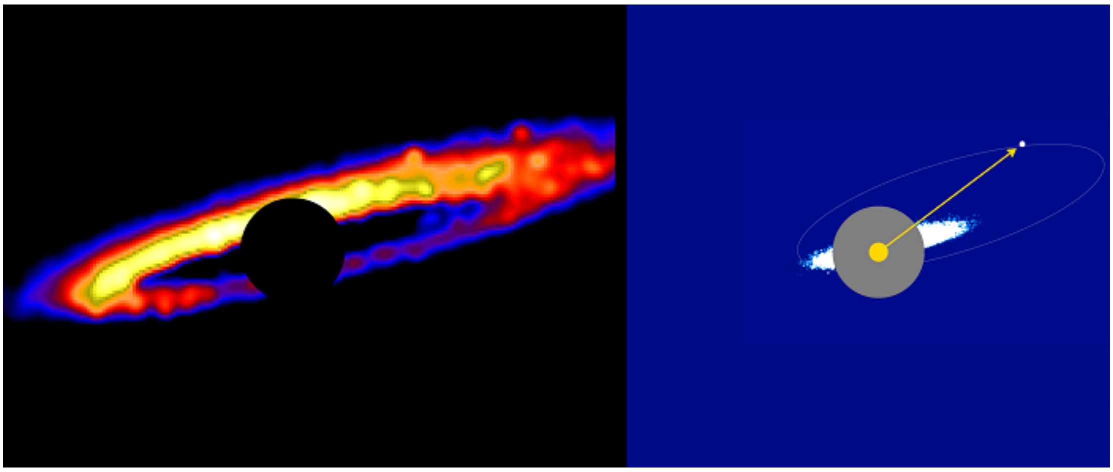

Figure 2: Two images of the HD 106906 stellar system created by Erika Nesvold and her team's simulation. The left panel shows a zoomed-in image of the ring of leftover rocky and icy planet-forming material that is rotating around the star. (The star is masked by the black circle.) The different hues represent gradients of brightness in the disk material. (Yellow is the brightest and blue the dimmest.). The right panel shows a farther-out view of the simulated system. The star is represented by the yellow circle with an arrow pointing to the exoplanet, 106906b. Nesvold's team demonstrated that the exoplanet is shaping the structure of the debris disk, which is shown by the white and blue dots encircling the star. (*Credit: Erika Nesvold*)

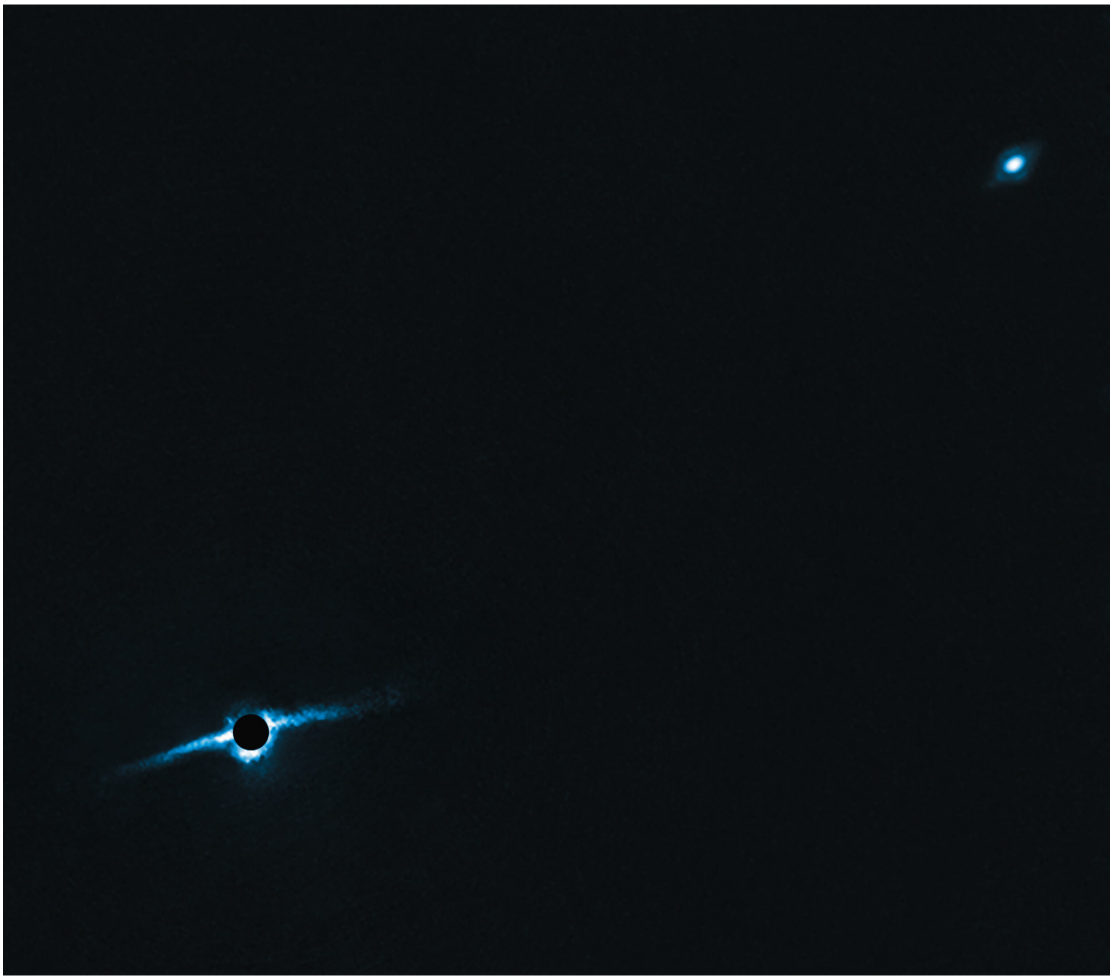

Figure 3: This is an actual observation of HD 106906 taken by the European Southern Observatory's planet-finding tool SPHERE. The star is blacked out by a circle (which masks its glare from blinding the instrument) and the debris disk can be seen in the lower left. In the upper right is the exoplanet, 106906b. The simulation created by Erika Nesvold and her team accurately recreated the observed characteristics of the disk: the disk is brighter on its eastern (left) side, and oriented about 20 degrees clockwise from the planet's position on the sky. (*Credit: ESO and A. M. Lagrange, Université Grenoble Alpes*)

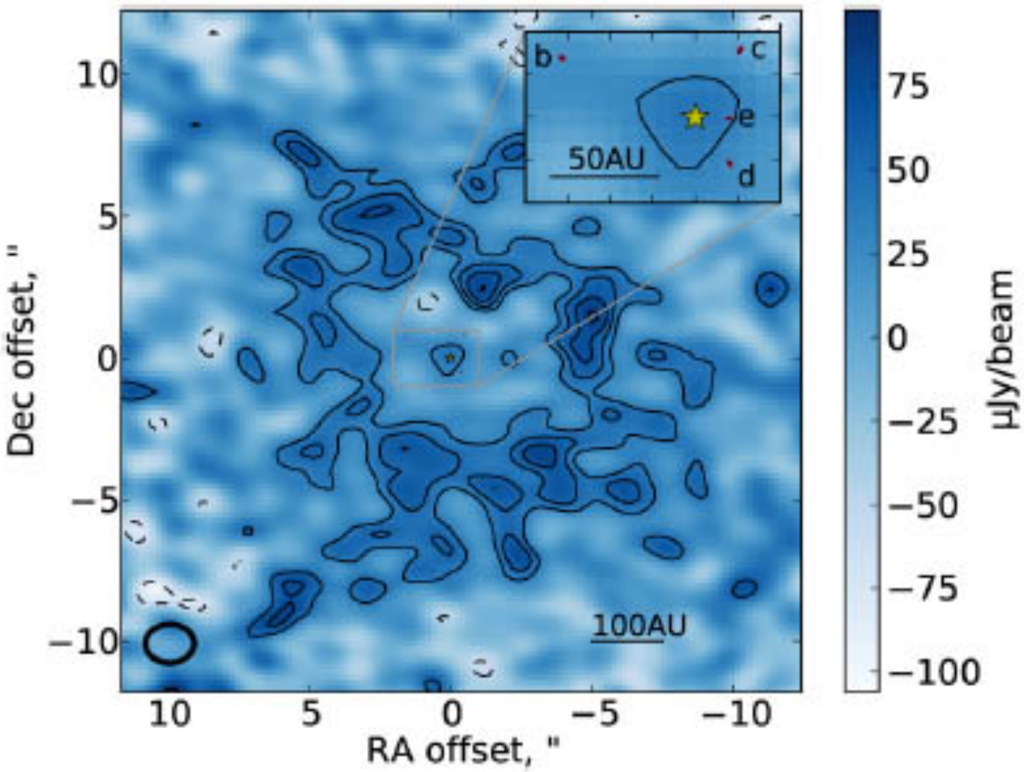

Figure 4: A submillimetre image of the planetesimal disk around the star HR8799, the first directly imaged system of four exoplanets and their dust disk. The insert shows the innermost region of the system and the location of the four exoplanets. (*Credit: ALMA; Booth et al.*)

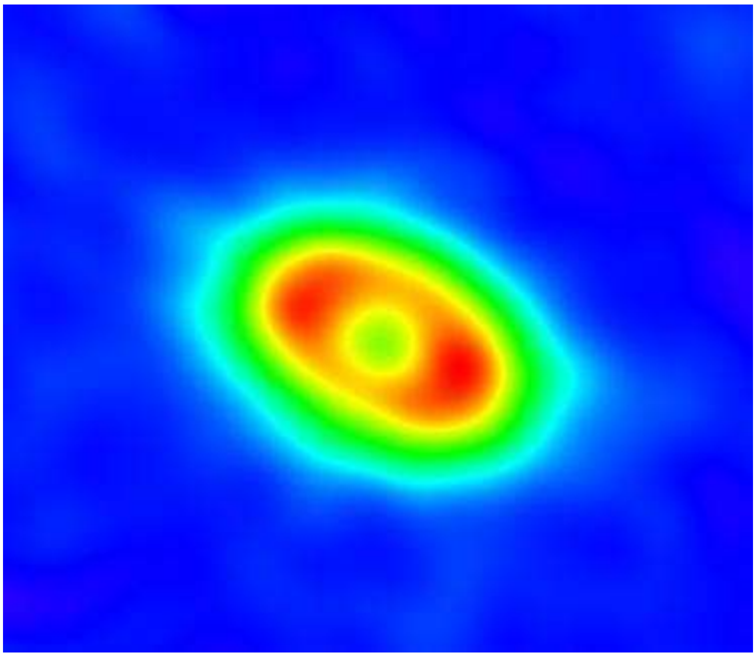

Figure 5: False-colour image of the circumstellar transition disk around the star LkCa15, taken at submillimetre wavelengths. A new study finds that the most probable explanation for the inner gap in transition disks is the influence of one or more giant planets orbiting nearby. (*Credit: S. Andrews*)

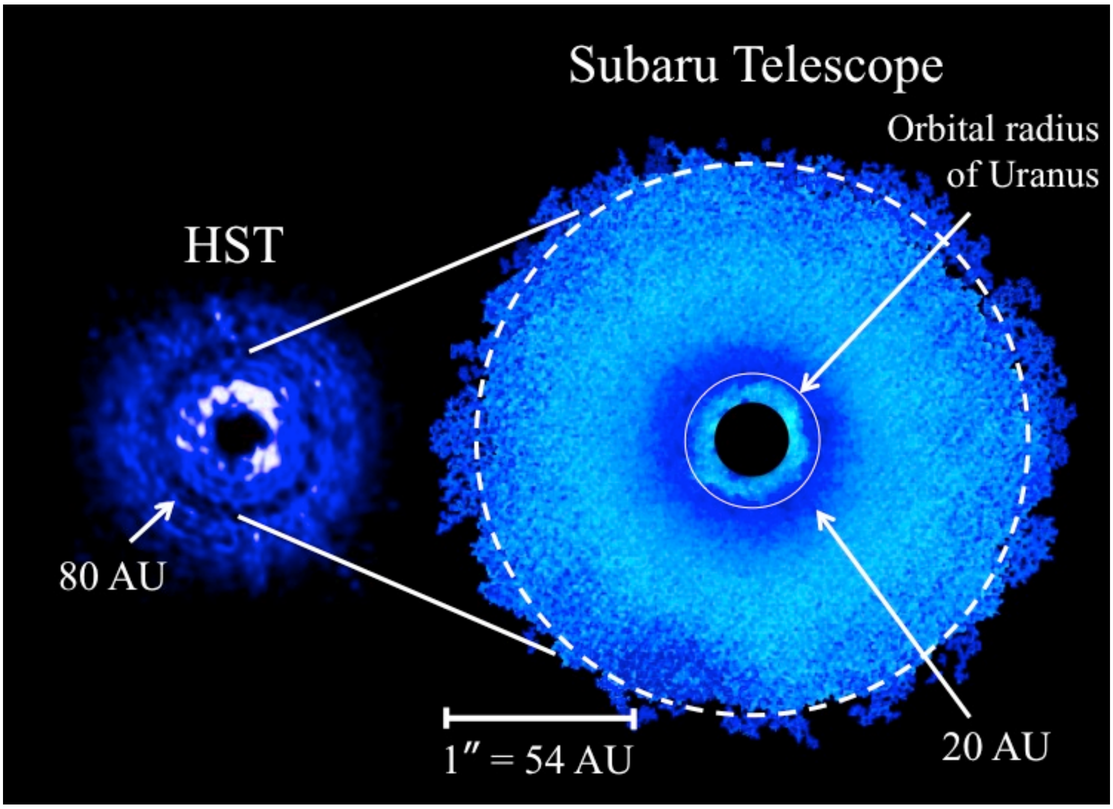

Figure 6: Protoplanetary disk around TW Hya. (Left) The near-infrared image obtained by the Hubble Space Telescope (HST) shows the ring-like gap at 80 au. (Right) Image taken by the Subaru telescope, shown with the observed HST radius of 80 au represented by a dashed circle. The orbital radius of Uranus represented by the thin solid line circle is superposed on the image for reference. The dark filled circle at the centre indicates a software mask with radius of 11 au. The ring-like gap was newly discovered at 20 au from the central star. (*Credit: NAOJ*)

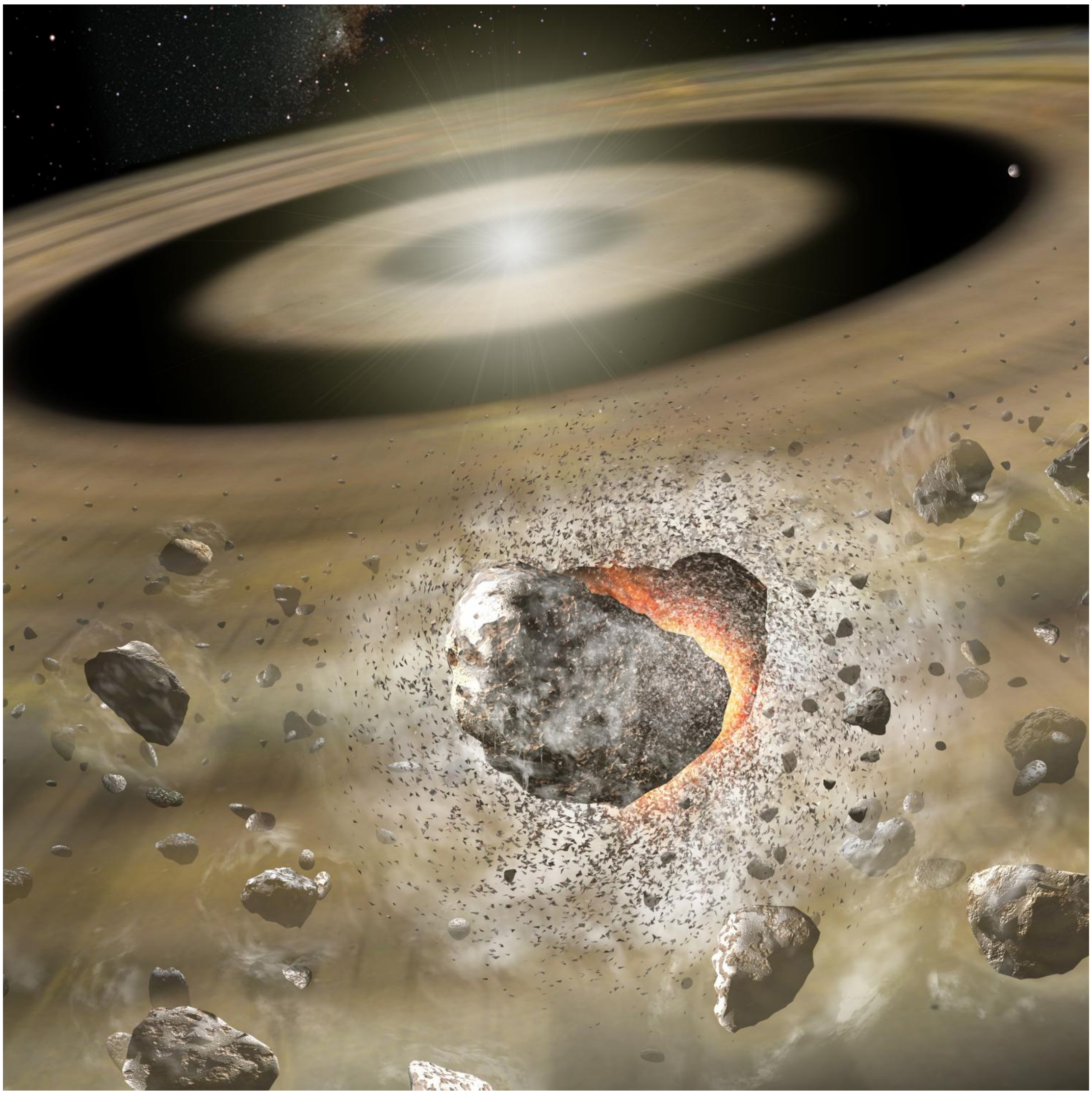

Figure 7: Artist's impression of gas generation from the collision between objects in a debris disk. (Credit: RIKEN)