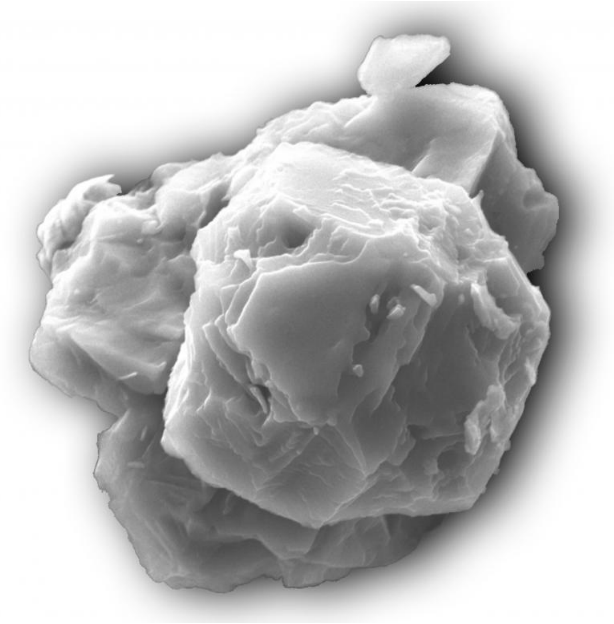
SUPERNOVAE AND INTERSTELLAR DUST

Online mini-workshop, April 12-14, 2021



NORDITA

Mike Barlow

THE DUST MASS IN CASSIOPEIA A DERIVED FROM INFRARED AND OPTICAL LINE FLUX DIFFERENCES

The large quantities of dust that have been found in a number of high redshift galaxies have led to suggestions that core-collapse supernovae (CCSNe) are the main sources of their dust and have motivated the measurement of the dust masses formed by local CCSNe. For Cassiopeia A, the oxygen-rich remnant of a Type IIb CCSN, a dust mass of 0.6-1.1 Msun has previously been determined by two different methods: (a) from a spatially resolved analsis of its far-infrared spectral energy distribution (De Looze et al. 2017) and (b) from an analysis of the red-blue emission line asymmetries in its integrated optical spectrum (Bevan et al. 2017). We present a third, independent, method for determining the mass of dust contained within Cas A. In order to determine internal dust optical depths, the method compares the relative fluxes measured in similar apertures from [O III] emission lines in the far-infrared, which are unaffected by dust extinction, with its visual-region lines that are affected by dust extinction. Foreground dust extinction is taken into account. From the derived internal dust optical depths, corresponding internal dust masses can be obtained. Using this method, a dust mass within Cas A of at least 0.99+-0.10 Msun has been determined.

Jérémy Chastenet

THE DUST CONTENT AND POLARISATION OF CASSIOPEIA A AND ITS SURROUNDINGS

The supernova remnant (SNR) Cassiopeia A (Cas A) has long been a pivotal target to understand the production, destruction and composition of cosmic dust from supernovae. In an effort to constrain the composition and average size of freshly condensed supernova dust from polarisation data, we will present new SCUBA-2/POL-2 measurements of Cas A from the JCMT. We will focus on the polarisation of supernova dust, after correcting for the contributions from interstellar dust and synchrotron polarisation. We will compare our results to the work of Dunne et al. (2003) that found up to 30% polarisation from dust grains. We will also build upon the work of De Looze et al. (2017) to disentangle the emission of dust from the SNR itself, and the surrounding interstellar medium. New dust models (Hensley & Draine, in prep; update to THEMIS, Jones et al. 2017) will help us put constraints on the dust composition from the measured polarized signal.

Ilse De Looze

THE COMPETITION BETWEEN SUPERNOVA DUST PRODUCTION, INTERSTELLAR GROWTH AND SUPERNOVA SHOCK DUST DESTRUCTION PROCESSES IN NEARBY GALAXIES

Scaling laws of dust, HI gas and metal mass are crucial to our understanding of the build-up of galaxies through their enrichment with metals and dust. We analyse the scaling relations for a diverse nearby galaxy sample, and interpret them using a set of Dust and Element evolUtion modelS (DEUS) within a Bayesian framework to enable a rigorous search of the full N-dimensional parameter space. We find that the scaling laws can be reproduced with efficient supernova dust production, relatively low grain growth efficiencies, and long dust lifetimes. The origin of dust in our nearby galaxy sample contradicts earlier studies that require more than 90% of the dust to be produced through grain growth. Our results provide an important step towards solving the conundrum on whether or not grains can grow efficiently in the interstellar medium.

Luca Graziani

THE IMPACT OF VARIOUS STELLAR POPULATIONS ON THE ASSEMBLY OF DUSTY GALAXIES AT Z > 4

Recent observations at z >4 by the ALPINE survey, complemented by a growing number of dusty galaxies detected in the Epoch of Reionization, have confirmed that a significant amount of dust was present in galaxies evolving in the first Gigayears of our Universe. To explain the physical evolution of these young objects, theoretical models of galaxy evolution require both a detailed description of their stellar populations producing dust, and an accurate description of the dust lifecycle in their multi-phase ISM. In this talk I will introduce recent hydrodynamical simulations performed with the dustyGadget code (Graziani ,MNRAS 2020) and discuss the role of PISN, SNe, AGB stars in the early build-up of the dusty ISM of the first galaxies, emphasizing the importance of a detailed inclusion of updated dust production yields for each type of stellar populations (Marassi,MNRAS 2019). I will focus, in particular, on the low-metallicity regime typical of the first generations of stars (POPIII/POPII) and on the impact of the reverse shock process on the predicted dust mass.

Thiem Hoang

EFFECTS OF SUPERNOVA FEEDBACK ON THE SURROUNDING DUST

Photometric and polarimetric observations toward type Ia supernovae (SNe Ia) usually reveal unusual properties of dust grains, which cannot be explained by the standard interstellar dust model. In this talk, I will present our recent works on studying the effects of intense supernova radiation on surrounding dust. I will first discuss two important effects induced by radiative torques driven by SN radiation, including a new mechanism of dust fragmentation (namely rotational disruption) and a well-known grain alignment mechanism. I will then present our numerical modeling results of extinction and polarization of SNe Ia taking into account both grain alignment and rotational disruption induced by SN radiation. I will compare our model results with observational data and show that the obtained results could successfully explain the observed extinction and polarization data of SNe Ia.

Hiroyuki Hirashita

EFFECTS OF SUPERNOVA FEEDBACK AND DUST PROCESSING ON THE CIRCUM-GALACTIC DUST

Supernovae not only produce dust but also contribute to the loss of dust from galaxies through dust destruction and dust outflow. The outflow enriches the circum-galactic medium (CGM) with dust. We aim at developing a consistent model for the above effects of supernovae both in the central galaxy and in the CGM.

In this presentation, we introduce our hydrodynamic simulations in which we implemented the dust evolution through dust production and interstellar processing. In particular, our model includes the evolution of grain size distribution. The simulation results broadly reproduce the relation between dust-to-gas ratio and metallicity, the radial profile of dust-to-gas ratio and the extinction curves in galaxies. The simulations also enable us to examine the dust properties in the CGM. We find that the dust in the CGM is dominated by large grains, because large grains produced by stars are injected into the CGM by supernova feedback before being heavily processed by shattering.

We further compare the resulting grain size distributions in the CGM with the observed reddening curves in Mg II absorbers in the literature. The steep wavelength dependence of the observed reddening indicates the existence of small grains, which cannot be explained by the above simulations. We discuss the possibility of forming small grains via shattering of large grains in the CGM, emphasizing the importance of modeling the dust production and transport by supernovae (or supernova feedback) in a consistent manner with dust processing.

Peter Hoppe

DUST FROM SUPERNOVAE FOUND IN PRIMITIVE SOLAR SYSTEM MATERIALS

Primitive Solar System materials, such as primitive meteorites and interplanetary dust particles, contain small amounts of so-called presolar grains which formed in the winds of evolved stars and in the ejecta of stellar explosions [1]. Presolar grains carry large isotopic abundance anomalies, the nucleosynthetic fingerprints of their parent stars. Presolar minerals with stellar origins identified to date include silicon carbide (SiC), graphite, silicon nitride (Si_3N_4), oxides, and silicates. Most presolar grains formed in the winds of low-mass asymptotic giant branch stars; important contributions are evident for supernovae as well, ranging from a few percent of presolar SiC grains up to almost 100 % of (very rare) presolar Si_3N_4 grains. For the most abundant type of presolar (stardust) grains, the silicates, recent Mg isotope studies suggest that the fraction of supernova grains is significantly higher than previously thought, possibly more than 30 % [2]. This implies that supernovae delivered a major fraction of the stardust that went into the making of our Solar System. Chronological information on grain formation in supernova ejecta was obtained from Ba-isotopic compositions of supernova SiC grains, which indicate a surprisingly late (~20 yr) timescale for condensation [3].

[1] Zinner, E. 2014, in Meteorites and Cosmochemical Processes, ed. A. M. Davis (Amsterdam: Elsevier), 181.
[2] Leitner, J. & Hoppe, P. 2019, NatAs, 3, 725.
[3] Ott, U. et al., ApJ, 885, 128.

Mika Juvela

INTERSTELLAR DUST IN STAR-FORMING REGIONS

The dust properties vary significantly in the interstellar medium (ISM). This is evident as we follow the evolution from diffuse to molecular clouds and further to the star-forming cores. The main trends are thought to be associated with the growth of the dust particles and the formation of mantle structures, including ices. However, the current dust models are still not able to explain all observations.

I will revisit the evidence for grain evolution and describe recent studies of dense clouds where we combine observations of dust emission and scattering. Herschel satellite data trace the submillimetre emission of large-grains and provide estimates for cloud column densities and radiation field intensities. However, using the current dust models, radiative transfer simulations reveal a contradiction with the near-infrared (NIR) dust scattering and extinction measurements. The main conclusion is that in star-forming clouds the ratio of submillimetre and NIR dust opacities is significantly higher than in the dust models or in the more diffuse ISM.

The variations of dust opacity and opacity spectral index, and the tendency for high mid-infrared scattering efficiencies all show that, at the epoch of star formation, the dust has acquired very particular properties. This has implications also for studies of supernova dust production and dust reprocessing, and not only via the contamination of those observations by the line-of-sight ISM dust.

Sergio Martínez-González

DESTRUCTION OF DUST GRAINS BY SUPERNOVAE WITHIN BUBBLES

I will present our recent work on supernova blast waves ramming through pre-existent wind cavities. By means of three-dimensional hydrodynamical simulations, we have studied such situation for the case of individual massive stars and super star clusters. The blast waves are mostly reflected and penetrate only a very thin layer into the swept-up shell. As a result, pre-existent dust grains locked up in the swept-up shell remain largely unaffected. Not only that, but supernova-condensed dust grains are not efficiently destroyed as the remnants evolve in the very tenuous wind cavity, where gas-grain collisions are infrequent. As a result, core-collapse supernovae within sufficiently massive swept-up shells may at last inject more dust to the ISM than what the shocks they produce are able to destroy.

Mikako Matsuura

SPITZER AND HERSCHEL STUDIES OF DUST IN SUPERNOVA REMNANTS IN THE SMALL MAGELLANIC CLOUD

We report investigations of dust in the Small Magellanic Cloud (SMC) supernova remnants (SNRs), surveyed by the Spitzer Space Telescope and the Herschel Space Observatory. The SMC is located only at 60 kpc away. The density of the ambient interstellar medium (ISM) where the SNRs are colliding into, can be estimated. The ISM density can be one of the important factors for shock, caused by SNR and ISM interactions.

In the SMC, 27 SNRs are known, and 7 are detected by Spitzer or Herschel with possible three more detections. The detected SNRs tend to be of two types. The first type of SNRs is those plunging into relatively low-density ISM regions, and SNR-ISM interactions are traced as bow-shocks. The second type SNRs contain neutron stars, and the pulsar wind nebula energised by the neutron star is detected. As found in our Herschel studies of Galactic SNRs, the SNRs in high-density ISM regions suffer source confusions, which are the most limiting factor of SNR detections. No clear indication of age and SNR detections rate has been made within our limited number of sample.

Maria Niculescu-Duvaz

DUST MASSES FOR A RANGE OF SUPERNOVAE FROM MODELLING THE RED-BLUE OPTICAL LINE ASYMMETRIES

Large quantities of dust have been discovered in a number of high-redshift ($z>6$) galaxies and quasars. One hypothesis is that this dust is mainly formed in the ejecta of core-collapse supernovae (CCSNe). For this to be the case, it has been estimated that each CCSN would need to produce >0.1 $M_\odot$ of dust (e.g. Morgan & Edmunds 2004; Dwek et al. 2007). Dust masses for a large sample of CCSNe with a range of different types and ages are needed to deduce whether this can be the case.

Newly formed dust can produce red-blue asymmetries in optical emission lines (Lucy et al. 1989), which can be modelled using the Monte-Carlo code DAMOCLES (Bevan & Barlow 2016). Dust masses for several Supernovae have already been determined using this method (Bevan et al 2017, 2019,2020), with the Damocles dust masses for SN1987A and Cassiopeia A agreeing with cold dust mass estimates from fits to Herschel far-IR SEDs. (Matsuura et al. 2011, De Looze et al. 2017).

Utilising a rich sample of late-time optical supernovae spectra from our Xshooter and Gemini GMOS survey (Wesson et al. 2021. in prep), we model the red-blue asymmetries in a range of optical emission lines in 10 CCSNe with ages between 3-60 years, using DAMOCLES. The dust mass for most of the CCSNe in our sample has not been evaluated before. For some objects we track the dust mass evolution over multiple epochs, for example SN 1979C, SN 1996cr, SN 1986E, and SN 2012aw. For supernovae with good signal to noise emission lines we also rigorously evaluate the uncertainties on the model parameters using bayesian inference (Bevan et al. 2019a). The majority of our sample with detectable emission lines show broad asymmetric line profiles and have large dust masses, with up to 0.5 Msun being present in some of the older remnants.

Ambra Nanni

INVESTIGATING METAL AND DUST IN LOW-METALLICITY LOCAL AND HIGH-REDSHIFT GALAXIES

The chemical enrichment of the interstellar medium (ISM) of galaxies is regulated by several physical processes: stellar birth and death, dust growth and destruction, galactic inflows and outflows. Understanding the interplay of such processes is essential in order to study the rise of metals and dust in the Universe, and to interpret the available and future observations of space- and ground-based telescopes operating at infrared and sub-millimeter wavelengths (e.g. Spitzer; ALMA; JWST). In this talk, I will present the results of a recent investigation focused on low-metallicity galaxies, and specifically, Lyman-Break galaxies at the epoch of reionisation and local dwarf galaxies, which are considered to be the local counterparts of Lyman-Break galaxies. I will show how the comparison between model predictions and observations allows us to identify the most relevant physical processes driving the evolution of dust in these systems, and how the information of local galaxies can be employed to interpret the observations of Lyman-Break galaxies at $5<z<10$. We find that a fast enrichment in metals and dust from Type II supernovae, followed by dust removal through galactic outflow, is required to reproduce the observations, while destruction of pre-existing dust in the ISM operated by supernovae shocks has a limited efficiency. Dust growth in the ISM is instead not necessary in order to reproduce the observations of the galaxies under study.

Larry Nittler

ELECTRON-CAPTURE SUPERNOVA DUST IN THE SOLAR SYSTEM

The evolutionary end-stage for stars of 7-10 solar masses is uncertain, due to computational difficulties. They experience a “Super-AGB” phase in which they lose most of their envelope mass in strong winds. This phase is likely followed by explosion as an electron-capture supernova (ECSN) once the O-Ne core reaches a Chandrashekhar mass and electron captures on 20Ne lead to rapid heating and loss of degeneracy pressure support. Nucleosynthesis calculations indicate that ECSN could produce relatively large amounts of neutron-rich isotopes, including ones like 48Ca, 50Ti, 54Cr, and light r-process nuclides, which show a heterogeneous distribution in the Solar System. Nano-sized (<100-nm) presolar oxide grains with extreme 54Cr (and probably 50Ti) enrichments have been identified in the Orgueil meteorite and likely originated from one or more ECSN. The lifetime of stars in this mass range make them plausible sources of dust and neutron-rich matter in star-forming regions and super-AGB stars and ECSN thus may play a role in the formation and isotopic heterogeneity of the Solar System. A better understanding of the fates of stars in this mass range, especially with regard to dust formation and evolution processes, is needed.

Jeonghee Rho

NEAR-IR OBSERVATIONS OF CO AND DUST FORMATION IN SUPERNOVAE

A large amount of dust seen in high-z galaxies implies that dust formed in the early Universe. Core-collapse supernovae (ccSNe) occur just several million years after massive stars are born. The dust masses measured from several young supernova remnants (SNRs) are ~1 solar mass per SN, which is consistent with dust formation models and suggests that ccSNe could be important dust factories at high z. However, the dust mass estimated from SNe is two-orders of magnitude smaller than those from SNRs. To understand the gaps of dust mass between supernovae (SNe) and young SNRs, we have started a Gemini Target of Opportunity observing campaign to observe newly exploded supernovae in nearby galaxies.

We present the first example of eleven near-infrared (0.8 – 2.5 microns) Gemini spectra of Type IIP SN2017eaw in NGC6946 and Gemini and optical observations of Type Ic SN2020oi in the galaxy M100 and the broad-lined Type Ic SN2020bvc in UGC 9379. SN2017eaw presents one of the most template examples of the CO evolution in a Type II SN over an extended period. The SN2017eaw spectra show the onset of CO formation and continuum emission at wavelengths greater than 2.1 μm from newly formed hot dust, in addition to numerous lines of hydrogen and metals, which reveal the change in ionization as the density of much of the ejecta decreases. We also see the evidence of dust formation around day 125. The light curves (LCs) of Type Ic SN2020oi are consistent with a STELLA model with canonical explosion energy, 0.07 Msun Ni mass, and 0.7 Msun ejecta mass. The near-IR spectrum of SN2020oi at day 63 since the explosion shows strong CO emissions and a rising K-band continuum, which is the first unambiguous dust detection from a Type Ic SN. Non-LTE CO modeling shows that CO is still optically thick and that the lower limit to the CO mass is 0.001 Msun. The dust temperature is 810 K, and the dust mass is ~10^(-5) Msun. We explore the possibilities that the dust is freshly formed in the ejecta, heated dust in the pre-existing circumstellar medium, and an infrared echo. We present the implication of dust formation from the observed near-IR spectra from SNe. We discuss how to advance the study of dust formation in SNe with JWST, which offers CO fundamental and SiO molecular bands and mid-IR continuum together with the on-going near-IR campaign.

Rhonda Stroud

SEARCHING FOR INTERSTELLAR SIGNATURES IN NANODIAMONDS AND ORGANIC MATTER FROM CHONDRITIC METEORITES.

Meteoritic nanodiamond was the first mineral identified by laboratory analyses as a carrier of isotopic anomalies consistent with a formation history prior to our solar system. Products of supernova nucleosynthesis are present at trace levels in the nanodiamonds, although the average C and N isotope compositions are consistent with solar system values. Due to the small size of the individual nanodiamonds, ~ 2 nm on average, the isotopic composition cannot be determined on an individual particle basis to provide a clear indication of interstellar provenance. However, aberration-corrected scanning transmission electron microscopy (ac-STEM) enables the investigation of individual nanodiamonds and their impurities down to single atom scale, and offers the possibility to identify different populations of nanodiamonds by structural and compositional differences. The putative presolar nanodiamonds are also physically associated with organic matter in the matrices of carbonaceous chondrites. The meteoritic organic matter in turn can have N isotopic compositions best explained as the result of ion-molecule chemistry inherited from the proto-solar molecular cloud, or edges of the protoplanetary disk. This talk will present results from ongoing ac-STEM studies of meteoritic nanodiamonds, and meteoritic organic matter in search of preserved interstellar signatures.

Felix Priestley

OBSERVATIONAL CONSTRAINTS ON DUST DESTRUCTION IN SHOCKS

Theoretical models of dust destruction in both the forward and reverse shocks of supernovae often disagree by orders of magnitude. Modelling the infrared emission from shocked dust grains in supernova remnants can provide empirical data to constrain these models. With gas properties derived from X-ray data, grain temperatures in the Cassiopeia A reverse shock and the forward shocks of several interacting supernova remnants are too high to reproduce the observed far-infrared fluxes. These require an additional colder dust component, which for any reasonable model assumptions contains orders of magnitude more mass than the warm dust. Estimated gas-to-dust ratios suggest that nearly all the dust in the X-ray emitting material has been destroyed, whereas the cold dust component is consistent with negligible destruction rates. The multi-phase nature of the shocked dust and gas makes one-dimensional, uniform-density models inadequate for describing dust destruction by supernovae.

Arkaprabha Sarangi

THE TIMELINE OF DUST FORMATION IN CORE-COLLAPSE SUPERNOVAE

In this talk I will discuss the physical environment and the chemical processes that control the formation of dust grains in the SN ejecta. I will emphasize on the various aspects of different types of core-collapse supernovae, characterized by their properties such as initial compositions, explosion dynamics, progenitor mass, circumstellar matter and a few others, that define the timeline of dust formation. Among the scientific questions, the important ones that I would aim to address are the following: (a) Does the majority of the dust mass grow by early nucleation in the gas phase or accretion on the surface? (b) When/how does the transition from gas phase to solid phase happen? (c) Why is there so little hot dust present in the ejecta? (d) How does the presence of CSM influence the formation of dust in the supernova ejecta?

Franziska Schmidt

HYDRODYNAMIC SIMULATIONS OF DUST DESTRUCTION BY SUPERNOVA REMNANT SHOCKS

Sub-millimetre observations of galaxies at redshift $z > 6$ have revealed dust masses of up to 10^8 solar masses. As such systems are too young for significant dust enrichment by asymptotic giant branch stars to have occurred, core-collapse supernovae (CCSNe) have been suggested as possible alternative dust producers. This is supported by numerous observations of dust in young supernova remnants (SNRs) over the past decade, where dust masses of up to 0.1-1.0 solar masses have been measured. Dust grains around and inside the SNR are subjected to interactions with the forward and reverse shock respectively. This leads to various erosion and growth processes such as sputtering, grain- grain collisions, and ion-trapping which result either in the destruction of the grains or in a size reduction. The predicted dust survival rates for grains subjected to supernova shocks vary greatly from study to study and models tend to treat dust destruction during post- processing. In this study, we investigate the survival rates of dust in and around CCSN remnants using hydrodynamic simulations carried out with the publicly available AMR code AstroBEAR. For this purpose, we have developed the Dusty Grid model which allows us to incorporate the dust and the dust destruction mechanisms directly into the MHD code. Our simulation setup is an extension of the Cloud Crushing model from Silvia et al. (2010) featuring a collection of dense gas clumps embedded in a less dense ambient medium through which a shock propagates. We present our preliminary results featuring the Dusty Grid model combined with an extended Cloud Crushing setup and an oxygen cooling function tailored to replicate the conditions in Cassiopeia A.

Jonathan Slavin

THE EVOLUTION OF SUPERNOVA-FORMED DUST GRAINS INCLUDING STELLAR WIND AND MAGNETIC FIELD EFFECTS

Core collapse supernovae are known producers of interstellar dust based on infrared emission in young remnants. The dust is believed to be created within the dense knots of ejecta which are embedded within a smoother background of lower density ejecta, as can be seen for example in Cas A. The ultimate fate of the grains that are created in these environments is still uncertain, however, since they need to make their way from the inner regions of the supernova remnant out past the reverse shock in order to seed the interstellar medium (ISM). We present results from calculations of dust evolution for grains originating in dense ejecta, which include the decoupling of the grains from the gas and the erosion of the dust by sputtering on its way out of the remnant. We find that grains can escape the remnant if they are large enough, though they lose a significant fraction of their mass along the way. Newly included in results presented in this talk are the effects of pre-supernova processing of the circumstellar medium by the stellar wind and the magnetic field in the surrounding ISM.

Miikka Väisälä

WHAT CAN A SUPERNOVA DRIVEN DYNAMO TELL US ABOUT POLARIZATION OF DUST IN OUR GALAXY?

Supernova-driven turbulent dynamo is a suggested mechanism for generating galactic magnetic fields. Gent et al (2013) performed supernova turbulence simulations in a local shearing box approximation to examine a dynamo generation of galactic magnetic fields. Based on those simulation results, we performed radiative transfer modelling with polarized dust continuum emission assuming simple magnetic alignment of the dust grains. These results were compared to Planck satellite observations of large-scale polarized emission, by situating the point of the virtual observer within the MHD model and generating simulated polarization maps. We particularly focused on the distribution of polarization fraction p and polarization angle dispersion S. We found p-S relation with similar slope to the Planck results and polarization angle dispersion has similar filament-like structure to that of the Planck observations. Our results support the idea that some large-scale reduction of polarization fraction is due to the turbulence of the diffuse galactic medium. Our polarization angle dispersion is reflective of the large-scale mean field generated by the dynamo, and we suspect that the filament-like structure of polarization angle dispersion is reflective of the small-scale structure of the galactic turbulence, but details of it are still not clear. What we can confirm is that they have absolutely no meaningful correlation with the distribution of shock fronts left behind by supernovae - which is not surprising as the structure of the MHD turbulence is connected to the whole dynamo process and not just local isolated features.

Roger Wesson

OBSERVATIONAL LIMITS ON THE EARLY-TIME DUST MASS IN SN 1987A

Dust masses of several tenths of a solar mass have been confirmed in recent years in the remnants of a number of core-collapse supernovae. When this dust forms is currently poorly constrained. While observational studies generally indicate that dust forms over many years post-explosion, theoretical studies find that dust formation should be complete within less than 1000 days.

We reconsider the ejecta of SN1987A, in which the dust mass is currently at least 0.4Mo. We have constructed a large grid of models to predict both the spectral energy distribution and optical emission line profiles, 800 days after explosion, for a wide range of dust properties. The differing constraints available from the SED and the line profiles strongly favour a dust mass of around 0.001Mo at this epoch. Models with much higher dust masses may reproduce the SED, or the emission line profiles, but cannot reproduce both. This work thus favours the slow dust-formation scenario, in contrast to theoretical dust-formation models.