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CSM interaction and dust formation in SN 2010jl

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Abstract. The origin of dust in galaxies >1 Gyr old has remained an unsolved mystery for over a decade. One proposed solution is dust produced by core collapse supernovae (CCSNe). Theorists have shown that 0.1-1 $M_{\odot}$ of dust must be produced per supernova for this to work as an explanation for the dust in young galaxies. SN 1987A has produced ~1 $M_{\odot}$ of dust since its detonation. However, most supernovae have been found to only produce $10^{-4} - 10^{-2}$ $M_{\odot}$ of dust. The energetic type IIn SN 2010jl is located in UGC 5189, in a dense shell of CSM. As dust condenses in the SN ejecta, we see, (1) a sudden decrease in continuum brightness in the visible due to increased dust extinction, (2) the development of an infrared excess in the SN light curve arising from dust grains absorbing high-energy photons and re-emitting them in the infrared, and (3) the development of asymmetric, blue-shifted emission-line profiles, caused by dust forming in the ejecta, and preferentially extinguishing redshifted emission. A dense circumstellar material (CSM) may increase the dust production by supernovae. We observe signs of strong interaction between the SN ejecta and a dense CSM in SN 2010jl. SN 2010jl has been a source of much debate in the CCSN community, particularly over when and how much dust it formed. The light curve shows strong signs of dust formation after 260 days. Arguments over these subjects have been based on the evolution of the light curve and spectra. We present new optical and IR photometry, as well as optical spectroscopy, of SN 2010jl over 2000 days. We estimate dust masses using the DAMOCLES and MOCASSIN radiative transfer codes.

Key words. circumstellar matter, dust, extinction, supernovae: general, supernovae: individual: SN 2010jl

1. Introduction

Following a supernova explosion, the hot ejecta expands outward into space and cools. The ejecta will become cool enough after ~1-2 years for dust to condense from the metal heavy gas. If the SN is surrounded by CSM, the ejecta slams into the CSM and generates a forward and reverse shock. Between these two shocks is a growing region known as the Cool Dense Shell (CDS) (Chevalier & Fransson 1994). The CDS may allow for more rapid cooling and condensation of dust particles (Ofek et al. 2014). As dust condenses in the SN ejecta, we expect: a sudden decrease in optical brightness due to increased dust extinction, an infrared excess in the SN light curve arising from dust grains absorbing high-energy photons and re-emitting them in the infrared, and asymmetric, blue-shifted emission-line profiles, caused by dust forming in the ejecta, and preferentially extinguishing redshifted emission(Sugerman et al. 2006).

From IR luminosities, huge dust masses of $\sim 10^8$ $M_\odot$ have been found for 3 galaxies at z > 6 (Bertoldi et al. 2003). A more recent observation at z = 8.38, contained 6x10^6 $M_\odot$ (Laporte et al. 2017). These dust masses could be even higher when we consider cold dust component (Omont et al. 2001). Large dust masses at high redshifts implies efficient dust formation took place in the first ~0.7 Gyr, giving a net dust production rate of ~ 1 $M_\odot$ yr^{-1}. This is too early for grains to be produced in the winds of low-mass stars (Bertoldi et al. 2003). If we assume the observed dust is a product of stellar processes, then it must have occurred through dust condensation in supernova ejecta and in the winds of high-mass stars (Bromm & Leob 2003). If that dust is made by SNe, then each SN must create a minimum mass of dust (0.1-1.0 $M_\odot$). This leaves astronomers with the task of measuring the amount of dust produced by each CCSN and determining if it's enough. To do this, we must assume nearby SNe will serve as suitable analogs because they are all we can observe. Many studies, by our group and others, find that only $10^{-4} - 10^{-2}$ $M_\odot$ of dust has formed in the 2-3 years after the SN explosion, the usual amount of time we spend observing them.

The discovery of ~ 1 $M_\odot$ cold dust in the ejecta of SN 1987A caused a re-evaluation of dust formation in CCSNe (Matsuura et al. 2011; Indebetouw et al. 2014). Studies by Gall et al. (2014) and Wesson et al. (2015) suggest that dust is continuously forming in the ejecta of CCSNe. Gall et al. 2014 used SN 2010jl as another example of efficiently forming dust in the ejecta material, saying it was on track to yield as much as SN 1987A. They also claimed that most CCSNe will follow a similar dust formation track.

SN 2010jl detonated on October 10, 2010 in UGC 5189, 48.9 Mpc away. The SN is located in a 10 $M_\odot$ "cocoon" of CSM (Zhang et al. 2012; Moriya et al. 2013; Ofek et al. 2014). It had a peak V band absolute magnitude of -19.9 (Zhang et al. 2012). It was a luminous, but not super-luminous supernova. This object has been extremely well studied, but there is no consensus on a complete model of its evolution.

2. Observations

Imaging and spectra were obtained with GMOS/Gemini South (GS-2012A-Q-79, GS-2013-Q-93, GS-2014A-Q-70, GN-2016A-Q-85). We have also obtained some early time BVRI magnitudes taken with the KPNO 1.2 m telescope. The data have been corrected for foreground extinction of E(B-V) = 0.027. We also obtained 10 epochs of Spitzer data from 2011 to 2017. These are images at 3.6 and 4.5 μm. Pre-explosion IRAC images of UGC 5189A were also available in the Spitzer archive from 27 December 2007 (Program 40301, PI Fazio) which were used to subtract from the SN 2010jl images to get accurate photometry. I presented the evolution of the 3.6 and 4.5 μm data, which showed that the peak of the black body moved to longer wavelengths at around 900 days. Between days 250 and 450, something powers an increase in the IR. This could be a sign of dust formation. Unfortunately, there is a gap in the observations in this 200 day window. There were non-detections in 11.1 μm images from SOFIA and VLT/VISIR data obtained in the B10.7 filter (10.65 μm). These provided us with an upper limit of 2 mJy (Wesson et al. 2015). We use this to rule out a 100 percent Si dust composition during modeling of the SED. From a light curve of the V, J, K, 3.6, and 4.5 bands (supplemented by data from Fransson et al. 2014) we see up to 250 days, the data are fit perfectly by a cooling curve for flash heated dust (Dwek 1983). This should rule out significant dust formation before 1 year.

Despite the large volume of observations for SN 2010jl, there are still multiple interpretations of the data. Authors cannot agree on whether the line profiles are asymmetric, if the line asymmetries are due to extinction by dust, when the dust started forming and how much there is, or if dust is forming at all. For example, there is a recession in the blueshift of the Hα line with time (Jencson et al. 2016). Multiple authors have pointed out that reddening by dust should lead to a decline in luminosity and progressive blueshift of the spectral lines. However, a decreasing blueshift can be explained by the dust shell expansion causing a drop in optical depth.

3. Radiative transfer modelling

I use two models to recreate what is happening with the SN ejecta's gas and dust. The first model recreates the IR blackbody emission from the dust, caused by absorption of optical light emitted from the gas. The second is recreating the dust's effect on gas's optical emission line profiles through scattering and absorption.

We use the MOnte CArlo SimulationS of Ionized Nebulae (MOCASSIN). MOCASSIN is able to model different dust environments in 3D. We use a grain size distribution of MRN grain ($a^{-3.5}$, 0.005-1 μm). The fit contains optical and IR components based on smoothly distributed carbon dust in a shell around the supernova site. The models use 100 percent amorphous carbon dust. We didn't include silicate dust with upper bounds on the 10 and 18 μm data from VLT/VISIR. There have been non detections of silicate emission with Sofia at 1300 days. Dust temperatures also indicate the dust must be mostly carbon based. The output includes a total dust mass, but our solutions are not unique. We ran MOCASSIN with the dust in a clumpy spherical distribution, which returned higher masses than the smooth shell. I also use a quick and dirty version of MOCASSIN called quickSAND. quickSAND is not a Monte Carlo simulation, but purely analytical. This allows me to cover my parameter space and narrow down on a solution much more quickly. I then take the solution from quickSAND and enter it in to MOCASSIN.

The emission line spectra obtained for 2010jl are modeled with the DAMOCLES code developed at UCL. This code uses a Monte Carlo grid method and can model a time sequence of observations of line profiles, e.g., Hα, Hβ, etc. It treats the absorption and scattering of line photons, along with the frequency shifts caused by repeated scatterings by moving dust particles. Observed line profiles can be fitted in order to obtain the total dust mass. It uses a tool called PLINY to optimize against variables that include the inner and outer radii of the ejecta, the density and velocity gradients in the ejecta, and the size range and power-law size distributions of different grain species. By combining the modeling for the H, [OI] and [OIII] lines, we can also better constrain the position within the remnant where the dust is formed. A major benefit of DAMOCLES is that my parameter space is more constrained.

4. Conclusions

I've run smooth shell models in quickSAND and MOCASSIN as well as torus models in MOCASSIN. These models have yielded dust masses on the order of 0.001 solar masses, with a clumpy shell increasing the dust mass. I've run DAMOCLES smooth shell, with yields consistently smaller dust masses than MOCASSIN. I'm currently working to resolve this discrepancy.

In conclusion, SNe might explain the large amounts of dust seen in high redshift galaxies. SN 1987A supports this hypothesis. There is no consensus on what is happening in 2010jl. The SED fitting has so far provided higher dust masses than line profile fitting. This is a work in progress.

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