Infrared Light Echoes of Core-Collapse Supernovae in Close Binaries

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Supernova Infrared Light Echoes

• Circumstellar (CSM) and/or interstellar (ISM) dust absorbs supernova (SN) radiation and reradiates it in the infrared (IR). Dust is most efficiently heated by ultraviolet (UV) radiation so UV-bright SNe are needed to produce strong IR echoes. Type II SNe produce most intense UV radiation.

• Cas A is the youngest known remnant of a core-collapse (CC) SN in our Galaxy. IR echoes of this SN IIb have been found with Spitzer (Krause et al. 2005). **These Cas A infrared echoes are mostly powered by the early-time UV SN radiation** (UV "flash" - Dwek & Arendt 2008; Vogt et al. 2012).

• The CSM surrounding progenitors of Type II SNe is generally dusty, so in addition to ISM echoes such as observed now near Cas A, **CSM IR echoes are expected to be seen up to several years following the SN explosion**. Early (< 1 yr) IR emission is often attributed to light echoes, at later times freshly-formed SN dust might dominate IR emission.

• The CSM in close binaries is expected to be strongly asymmetric. Imprints of this asymmetry should be seen in IR echoes of those SNe II that exploded in close binaries.

Destruction and Heating of CSM Dust by the SN Radiation

• Dust condensing in red supergiant (RSG) winds is primarily made of **amorphous silicates** and **metallic iron grains**, together with smaller amounts of corundum and perhaps other less common dust species (e.g., Tamanai et al. 2017). Unlike in the ISM, little (if any) carbonaceous dust is expected!

• **Dust is vaporized by the SN radiation up to the vaporization radius r_V**, with smaller grains vaporized to somewhat larger distances from the SN than larger grains.

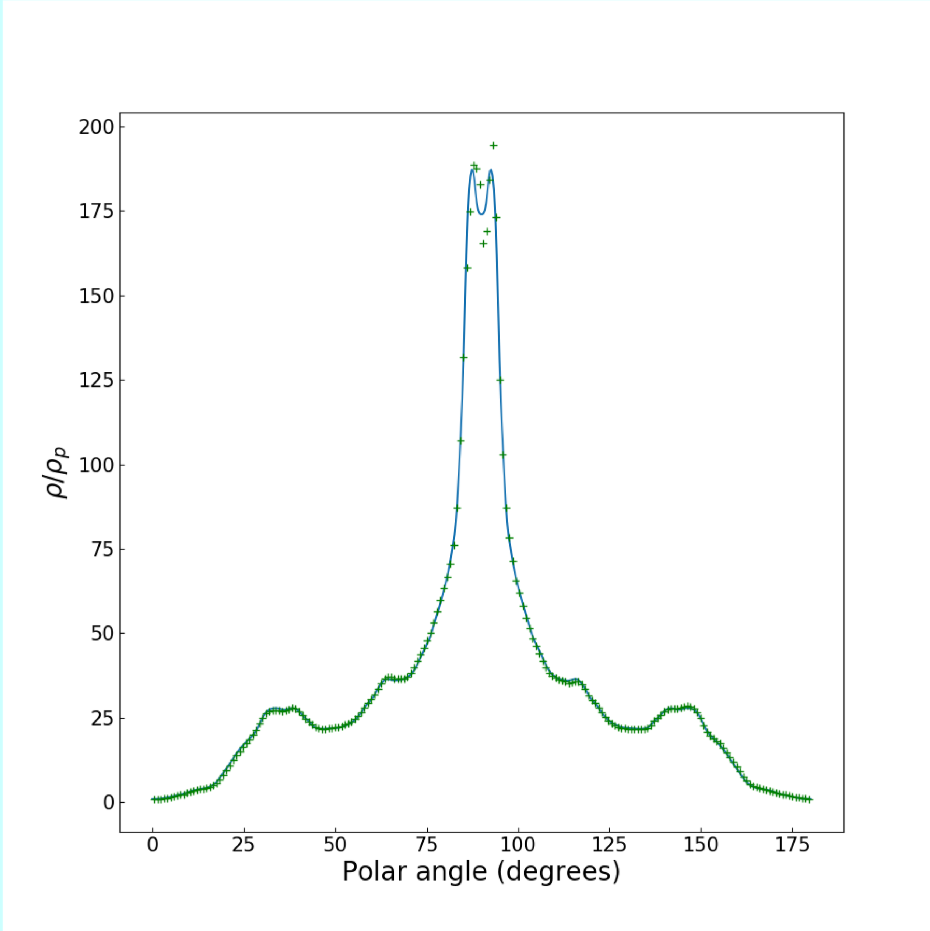
• Beyond r_V, **large grains are predicted to be rotationally disrupted into smaller grains** (Hoang et al. 2019). Small grains most efficiently absorb UV (but not optical) radiation.

•Dense CSM has been recently found in the immediate vicinity of most progenitors of Type II SNe. This greatly enhances UV radiation at early times following the SN explosion (e.g., Dessart et al. 2017; Moriya et al. 2018).

•To give an example, we took one of the models of Moriya et al.. a 12 solar mass RSG progenitor with the CSM mass of 0.089 solar masses , and considered **amorphous silicate** grains with radius of 0.05 microns. We estimate r_V at 0.10 pc, with grain temperatures there near 1790 K. **Silicate dust is heated primarily by UV "flash" radiation emitted within several days after the explosion**, in a qualitative agreement with observations of the Cas A IR echoes.

•Assuming a spherically-symmetric wind with mass-loss rate of 10^{-4} solar masses per yr, asymptotic wind speed of 15 km/s, and the dust/gas mass ratio of 0.003, we arrive at the dust optical depth of 0.15 at r_V=0.10 pc. The estimated IR luminosity at early times ($t <$ $\mathbf{t_V = 2r_V/c}$ = 240 days) is 6 million solar luminosities, within the observed IR luminosity range for CC SNe (e.g., Szalai et al 2019).

Asymmetric CSM



A representative CSM density distribution (green + signs) obtained in a 3D hydrodynamical simulation of outflows in close binary systems (for more details, see poster by C. Kolb). For this simulation, the orbital speed is twice as large as the wind speed. We used the averaged profile (solid line) (assuming mirror symmetry with respect to the equatorial plane) while modeling IR echoes.

Modeling of IR Light Echoes for Asymmetric CSM

• We use methods and techniques of Emmering & Chevalier (1988) who studied echoes produced by axisymmetric ellipsoidal CSM density distributions

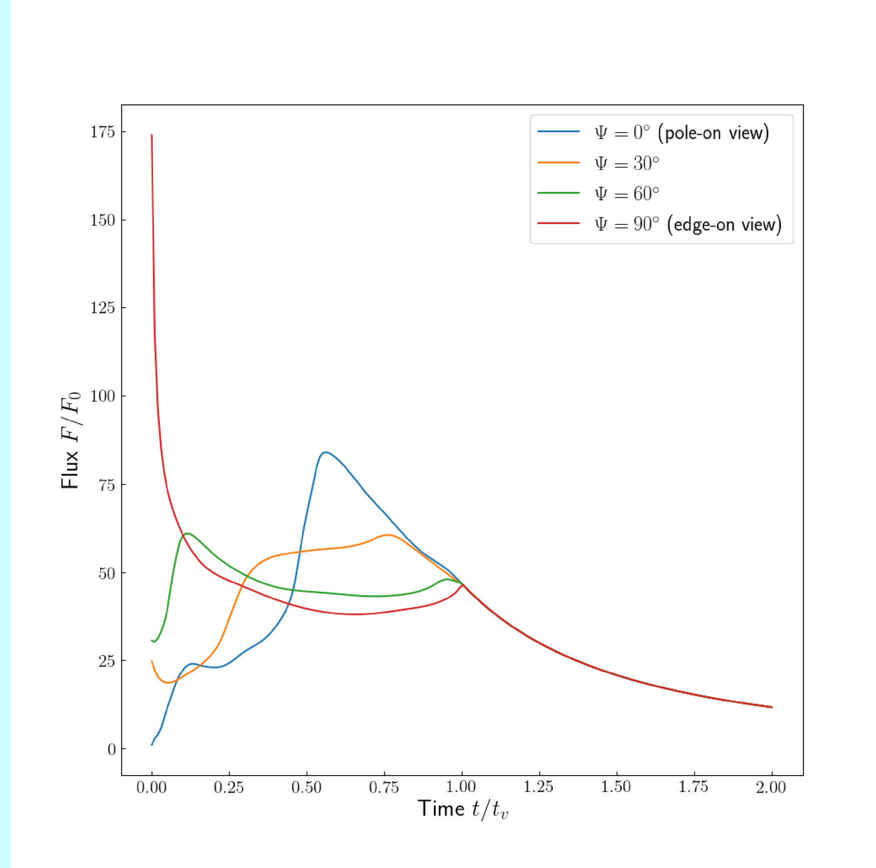
• **Steady-state wind** is assumed.

• The dust emission efficiency factor Q is assumed to be inversely proportional to wavelength. We consider only a **single grain size**.

• There is **no dust within the vaporization radius r_V**.

• We assume that IR echoes are produced by a pulse of radiation with constant intensity with duration much shorter than time $\mathbf{t_V = 2r_V/c}$ **(an infinitesimal pulse)**.

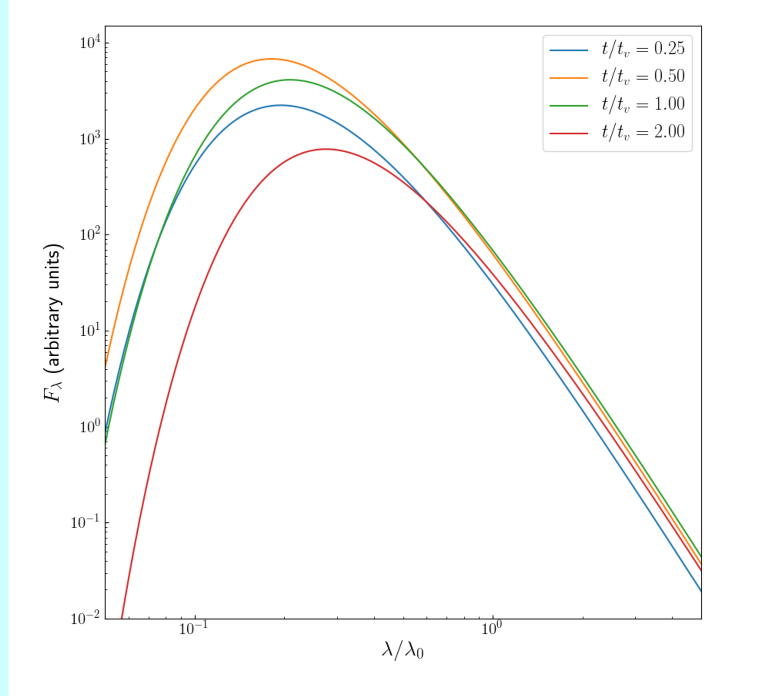
The Integrated Flux



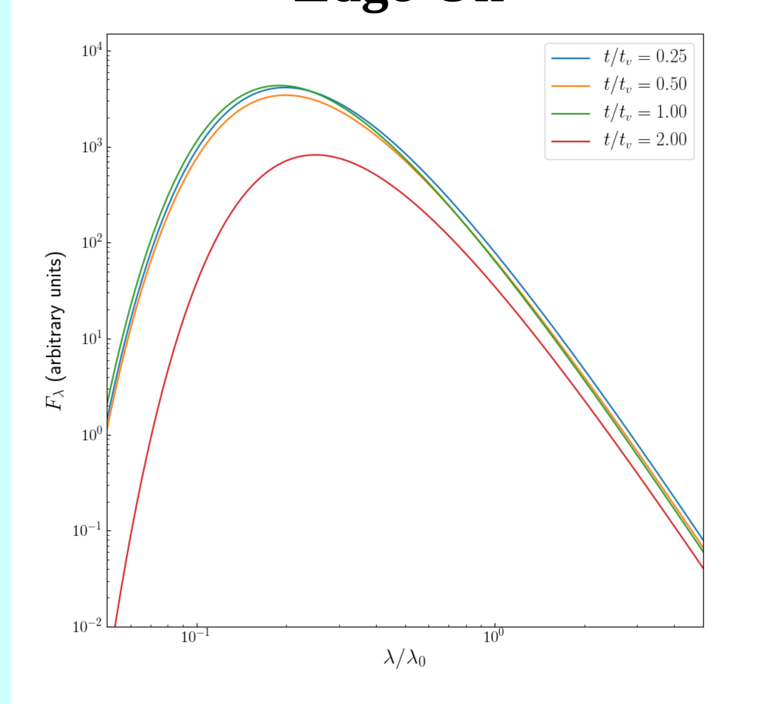
The integrated flux vs. dimensionless time t/t_V for several viewing angles (t_V is usually about several hundred days). Unlike for the SN ejecta dust, the echo emission is strong even at early times.

Infrared Spectra

Pole-On



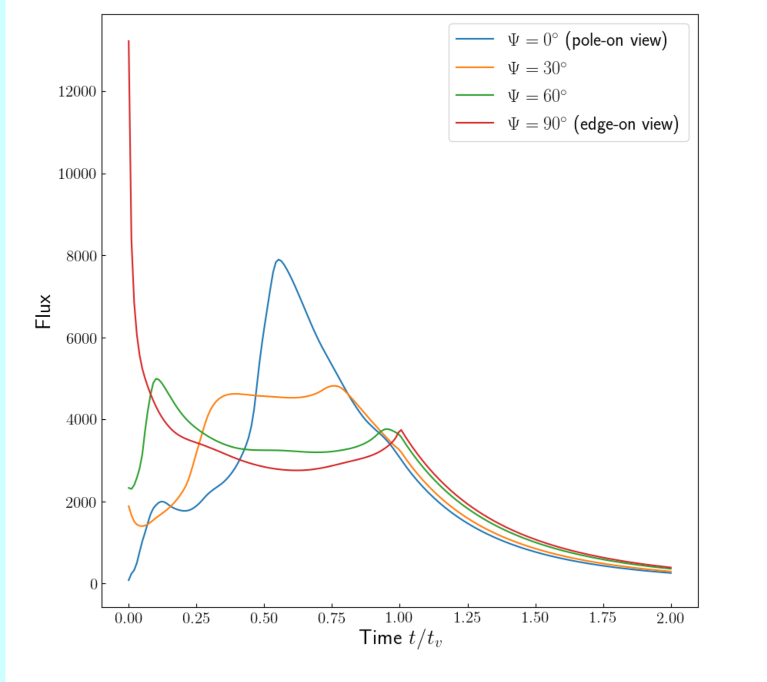
Edge-On



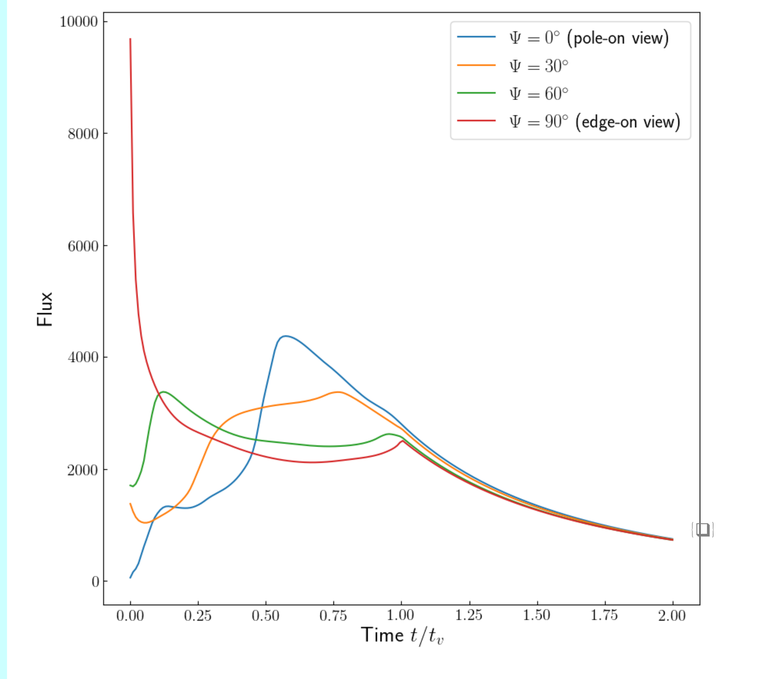
Pole-on (left) and edge-on (right) spectra at several times. The reference wavelength is equal to $(T_{d0}/1000\ K)^{-1}$14.4 microns, where T_{d0} is dust temperature at r_V. As expected, emission shifts to longer wavelengths at later times, but the spectral evolution is more complex early on.

Flux Variations at Selected Wavelengths

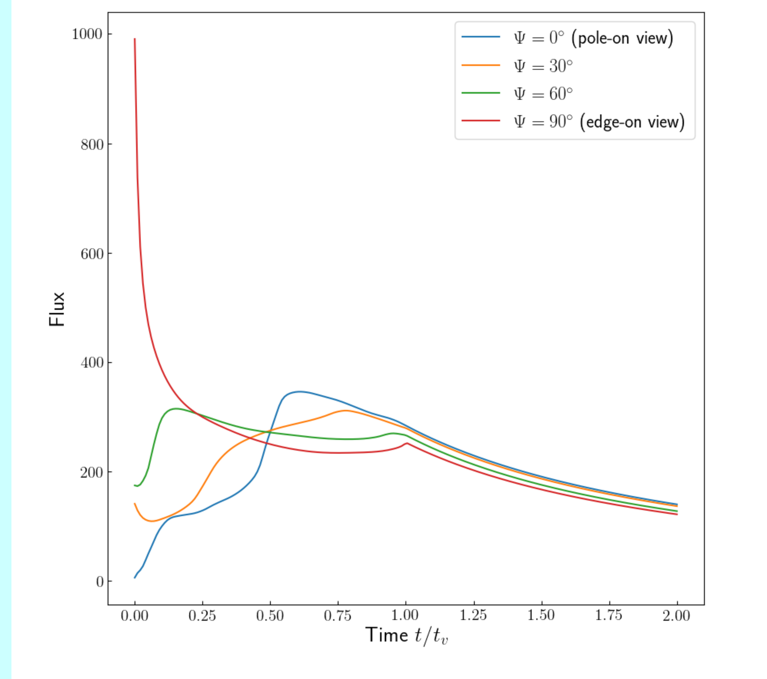
2.2 microns



4.5 microns



10 microns



Flux vs. time at $(T_{d0}/1000\ K)^{-1}$ 2.2 microns (left), $(T_{d0}/1000\ K)^{-1}$4.5 microns (middle), and $(T_{d0}/1000\ K)^{-1}$10 microns (right) for several viewing angles. Flux variations are most pronounced at the shortest wavelength (K band), and they gradually decrease with the increasing wavelength.

Conclusions

1. **IR echoes bear imprints of the strongly asymmetric CSM that is generally expected to be present around progenitors of Type II SNe in close binaries.**

2. **Early-time IR observations with Spitzer and the JWST are crucial for studies of the CSM density distribution, and for distinguishing between different origins of IR emission at late (> 1 yr) times (e.g., between emission from the freshly-formed ejecta dust and from pole-on views of IR echoes). Strong temporal variations of the IR echo emission at early times are not expected for the spherically-symmetric, steady-state stellar wind.**

3. **Observations of the Cas A IR echoes and some of the most recent models of the UV "flash" radiation in Type II SNe suggest that this UV flash both vaporizes and heats the CSM dust. If so, very hot CSM grains are expected, perhaps in apparent disagreement with observations of most CC SNe (Type IIn SN 2010jl is the notable exception; Fransson et al. 2012).**

4. **Future JWST observations of Type II SNe will enable studies of the silicate dust emission features near 10 and 18 microns. Since silicates are expected to be abundant in the CSM dust, these features must be present in spectra of IR echoes (our simple echo models do not include them). Their temporal variations relative to IR emission at shorter wavelength will provide constraints on the CSM density distribution around Type II SNe, particularly when combined with observational signatures of the CSM asymmetry at wavelengths other than the IR (e.g., at radio wavelengths).**

References

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