Dust Formation and Emission from Pulsar-Driven Supernovae

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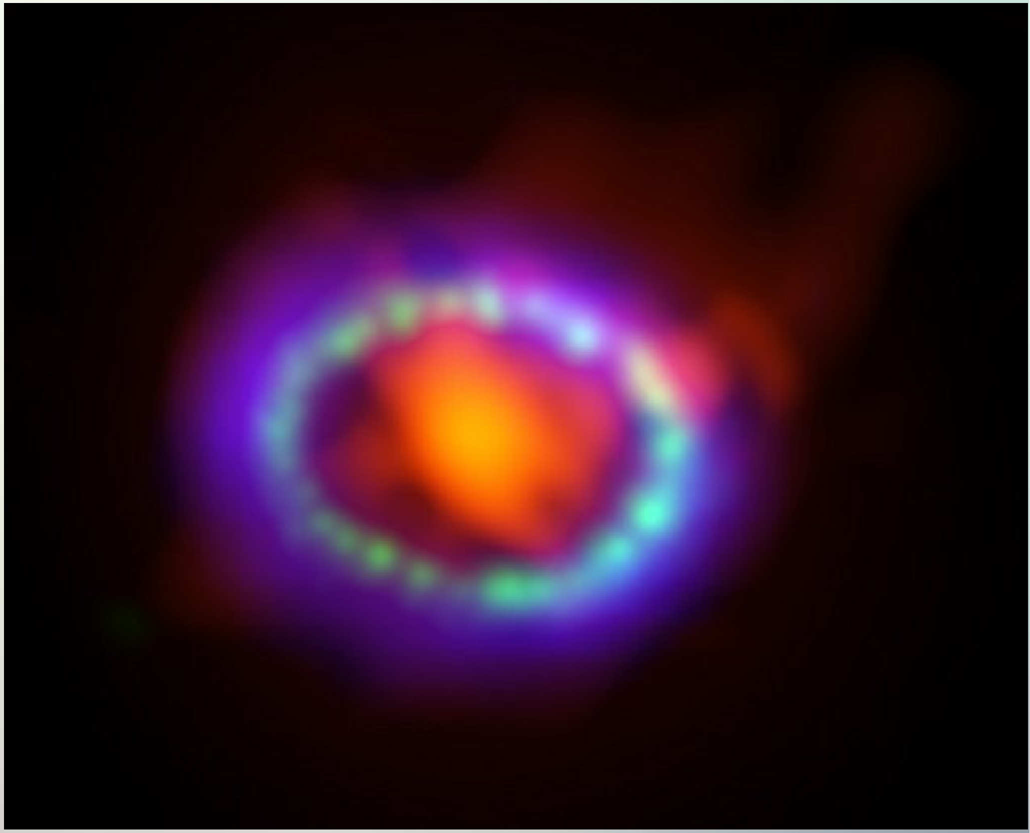
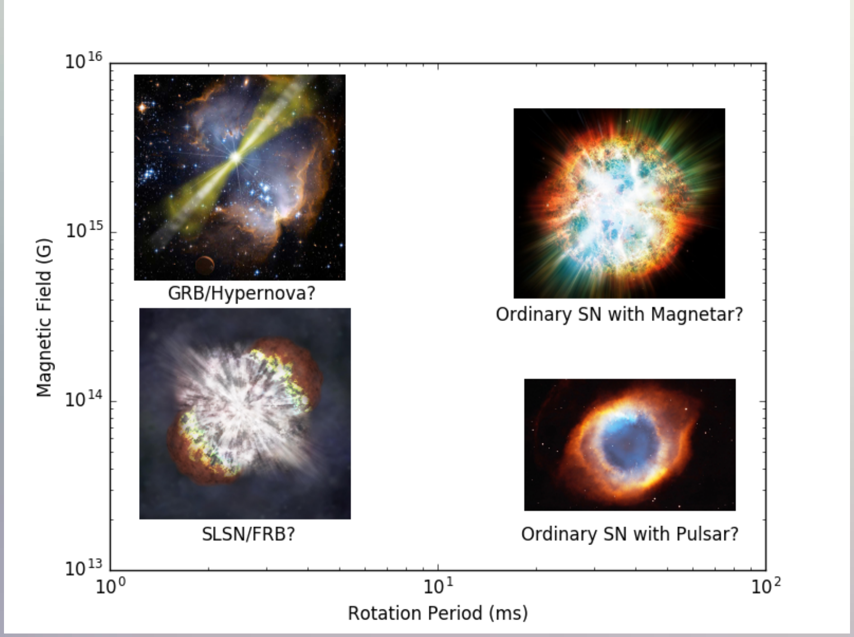
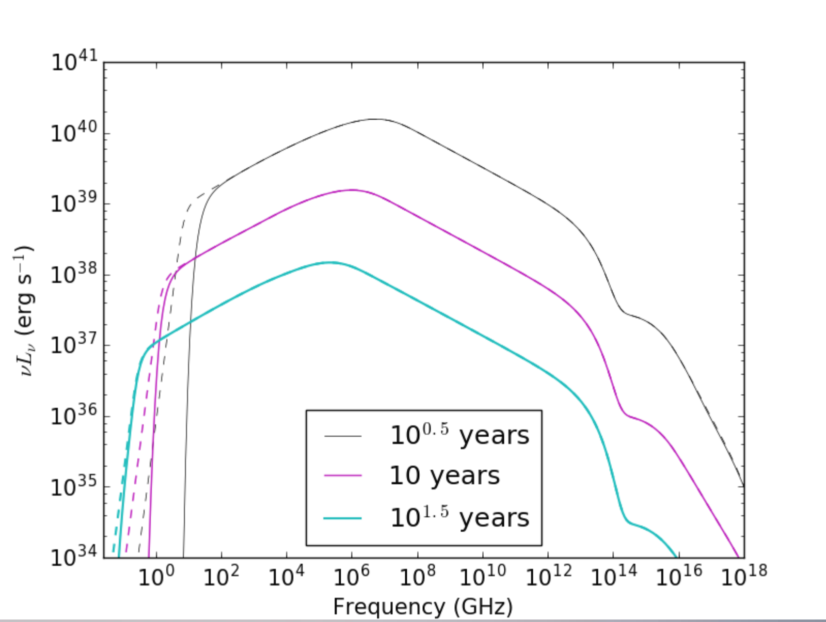


Credit: Alexandra Angelich (NRAO/AUI/NSF)

Background

- Models of pulsar-driven SN to explain energetic transients are common
- In order to test the pulsar-driven SN model, late-phase emission should be probed





Omand+, 2018

Purpose

- Dust has been found around SN, shown to cool quickly (SN1987A has ~20 K dust)
- If the dust absorbs optical/UV radiation from the PWN, it could heat up and emit in infrared
- Want to determine:
  - Which supernovae form dust?
  - How different parameters affect formation time, dust size, and temp?
  - What does the emission look like?
  - Are detections feasible?

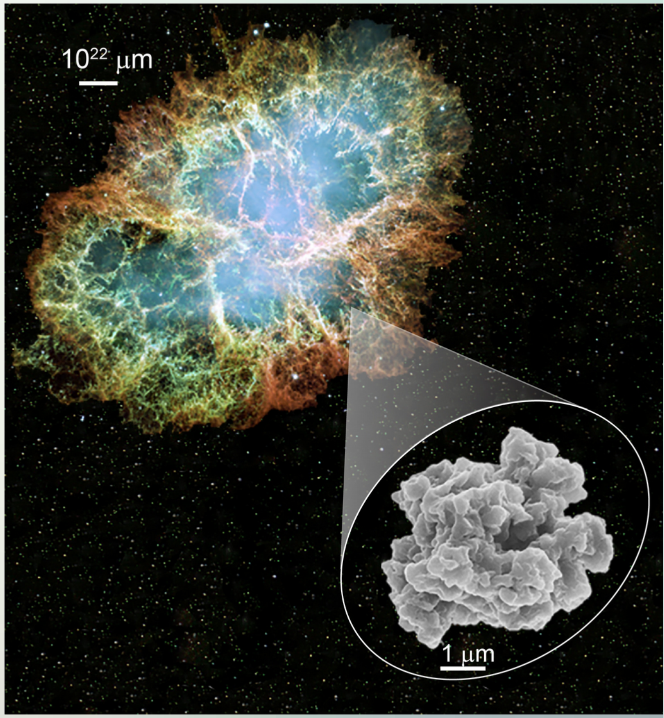


Image credits: NASA and Larry Nittler.

Strategy

- Calculate ejecta dynamics (Kashiyama+, 2016)
- Calculate dust formation and growth (Nozawa and Kozasa, 2013)
- Calculate dust temperature and account for sublimation (Waxman and Draine, 2000)
- Account for ionization
- Calculate blackbody/greybody emission from dust

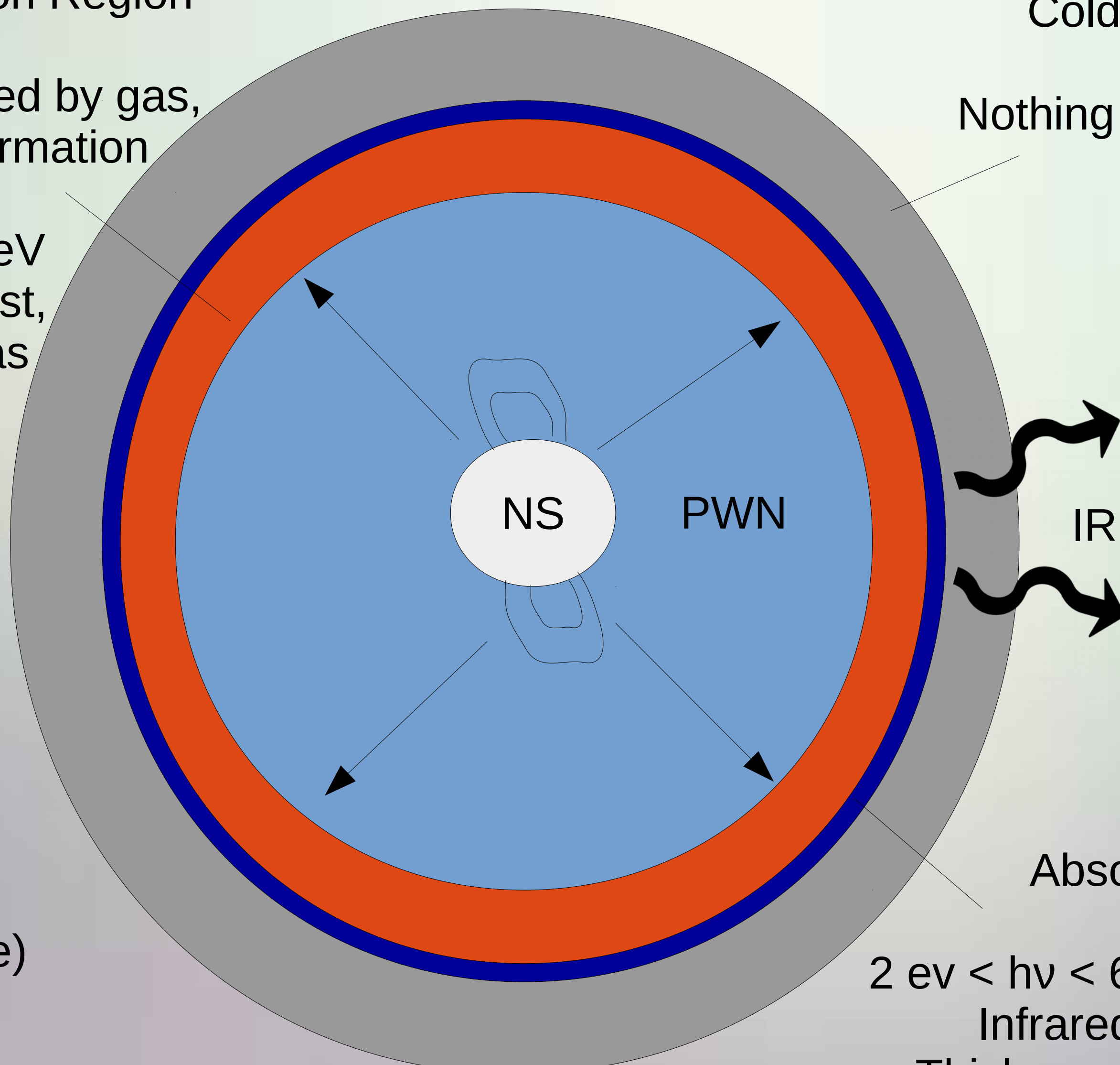
Model Overview

Ionization/Sublimation Region

hν < 11.2 eV absorbed by gas, preventing dust formation
- or -
2 ev < hν < 6 eV absorbed by dust, sublimating it as it forms

Cold Dusty Region

Nothing absorbed by dust
$\tau_{IR} << 1$



IR Emission

Absorption Region

2 ev < hν < 6 eV absorbed by dust
Infrared emitted by dust
Thickness given by $\tau_{opt/UV} \sim 1$

(Not to scale)

Dust Formation

- Dust grains form by nucleation of key molecules

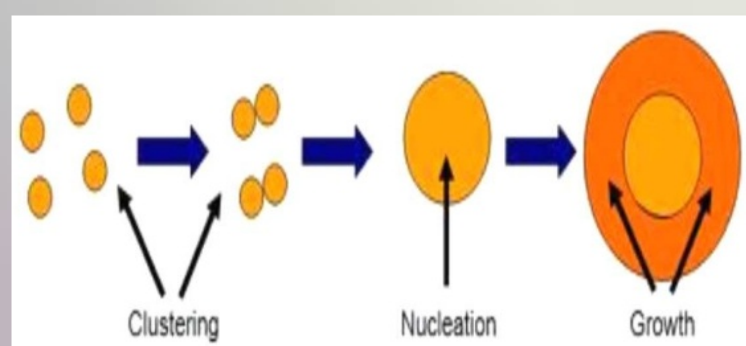
$$J_s = s\Omega_o \left(\frac{2\sigma_{\mathrm{ten}}}{\pi m_1}\right)^{\frac{1}{2}} c_1^2 \Pi \exp\left(-\frac{4}{27}\frac{\mu^3}{(\ln S)^2}\right)$$

- Nucleation controlled by supersaturation ratio *S*

$$\ln S = \frac{A}{T_{\mathrm{gas}}} - B + \ln\left(\frac{c_1 k_B T_{\mathrm{gas}}}{p_s}\right) + \ln \Xi$$

- Grains grow by accretion of key molecules

$$\frac{da}{dt} = s\Omega_o \left(\frac{kT_{\mathrm{gas}}}{2\pi m_1}\right)^{\frac{1}{2}} c_1 \left(1 - \frac{1}{S}\right)$$



Dust Destruction/Emission

- Dust is sublimated out to a critical radius:

$$R_c = \left(\frac{L_{\rm opt/UV}}{16\pi\sigma T_c^4} \frac{Q_{\rm opt/UV}}{\langle Q \rangle_{T_c}} \right)^{\frac{1}{2}}$$

- Opt/UV optical depth determines emission:
- Optically thick: $$L_\nu = 4\pi R_c^2 Q(a)\pi \frac{2h\nu^3}{c^2} \frac{1}{e^{\frac{h\nu}{k_B T_c}} - 1}$$
- Optically thin: $$dL_\nu = 4\pi r^2 n_{\rm dust} 4\pi a^2 Q(a)\pi \frac{2h\nu^3}{c^2} \frac{1}{e^{\frac{h\nu}{k_B T(r)}} - 1} dr$$

- Gas is ionized out to the Strömgren radius:

$$R_s = \left(\frac{3}{4\pi} \frac{S_*}{c_1^2 \beta_2} - R_{\rm ej}^3 \right)^{\frac{1}{3}}$$

Parameters to Study

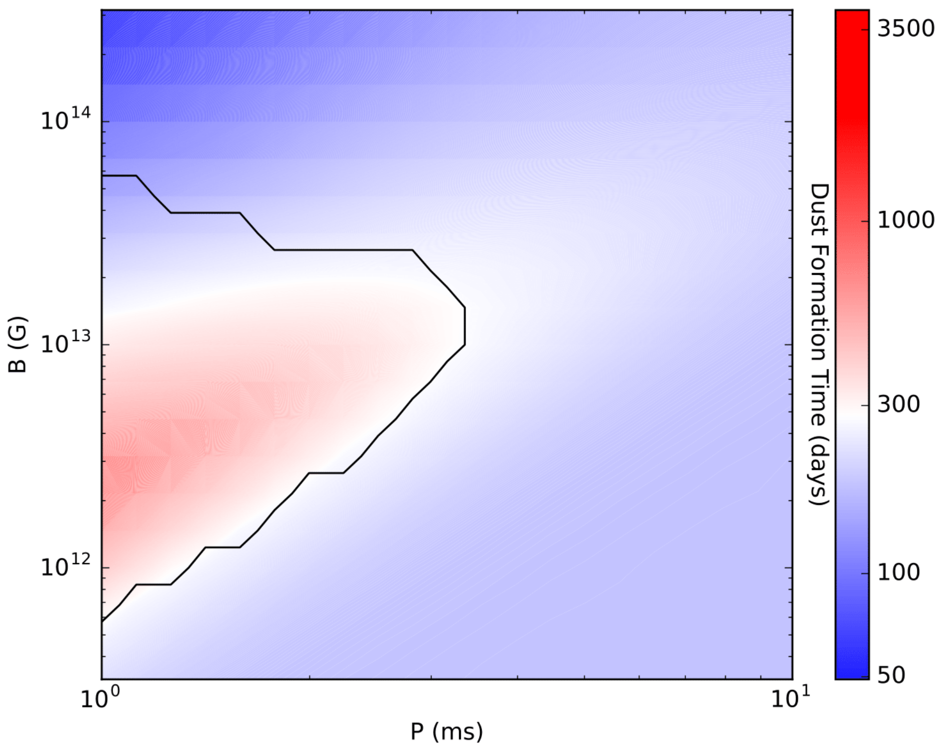
Composition	f_C	f_O	f_{Mg}	f_{Si}
B	0.1	0.3	0.03	0.03
C	0.3	0.6	0.05	0

Grain Type	$C_{(s)}$	$MgSiO_{3\ (s)}$	$MgO_{(s)}$
Key Species	$C_{(g)}$	$Mg_{(g)}$	$Mg_{(g)}$
$A/10^4$ (K)	8.64726	25.0129	11.9237
B	19.0422	72.0015	33.1593
a_o (Å)	1.281	2.319	1.646
σ_{ten} (erg cm^{-2})	1400	400	1100

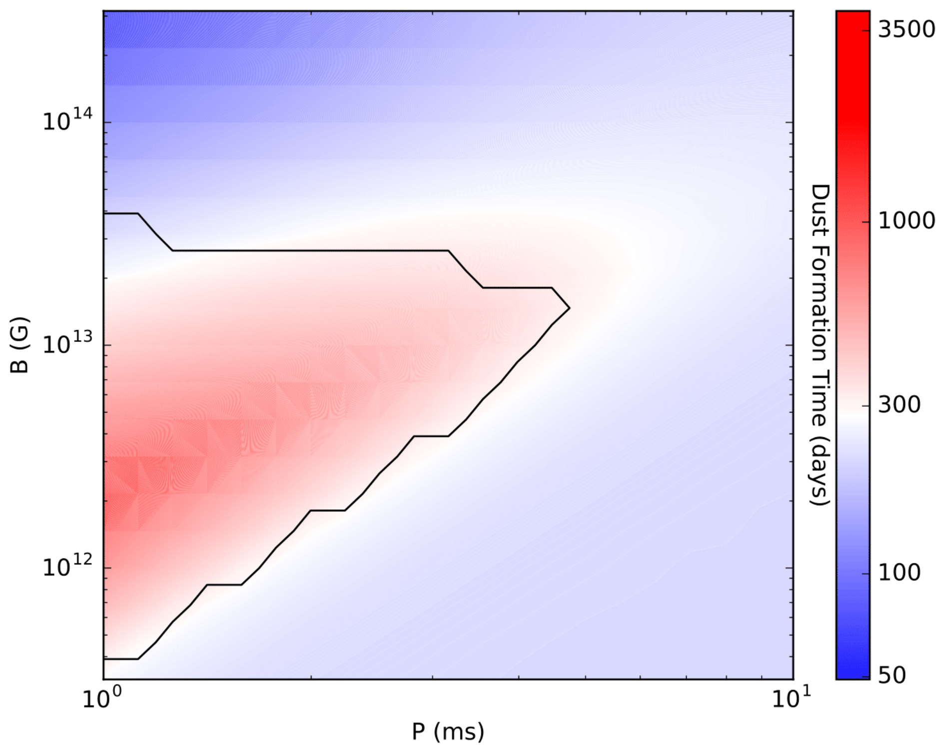
ID	Composition	M_{ej} ($M_\odot$)	f_L
B5-1	B	5	1
B5-05	B	5	0.5
B15-1	B	15	1
C5-1	C	5	1
C15-1	C	15	1

Formation Timescale (B5-1)

C

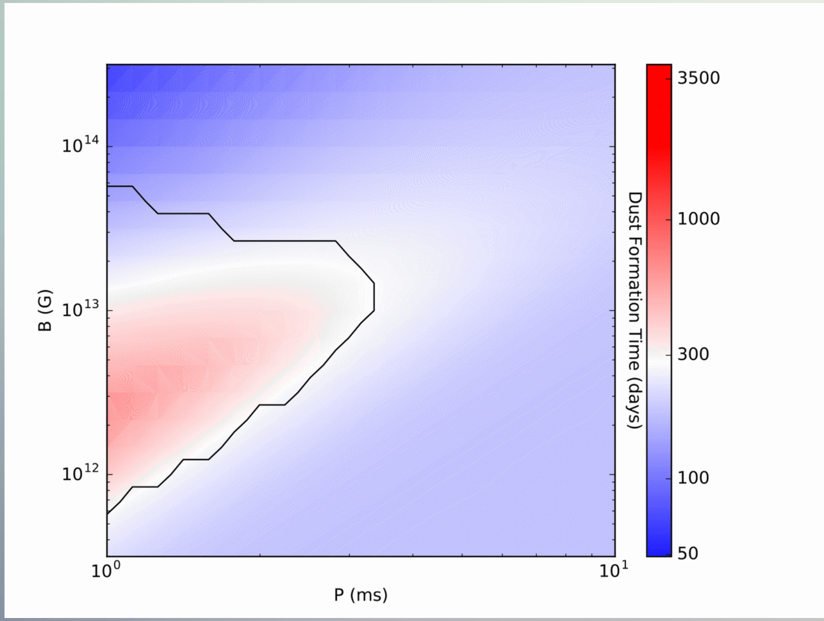


$MgSiO_3$



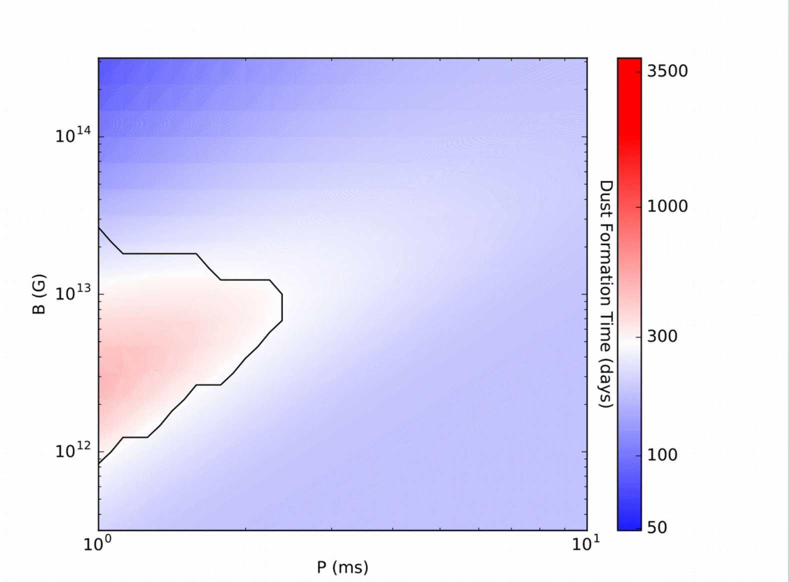
Formation Timescale (B15-1 and B5-05)

B5-1



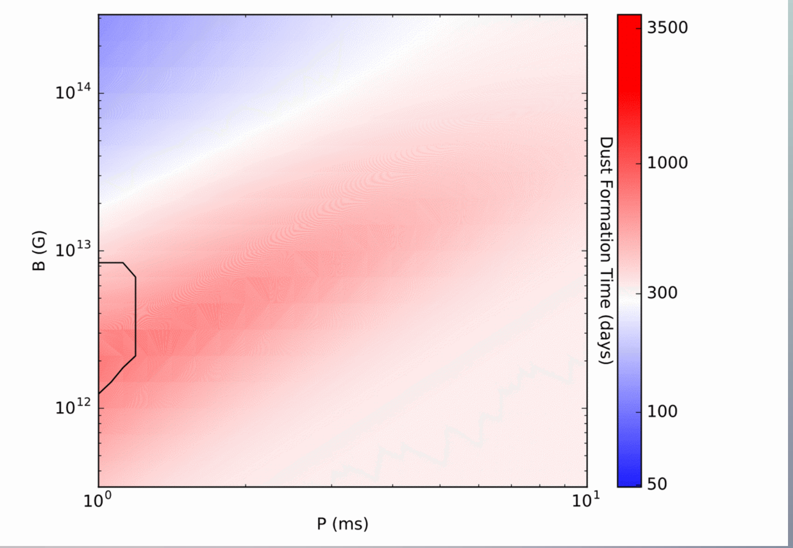
Decrease Luminosity

B5-05



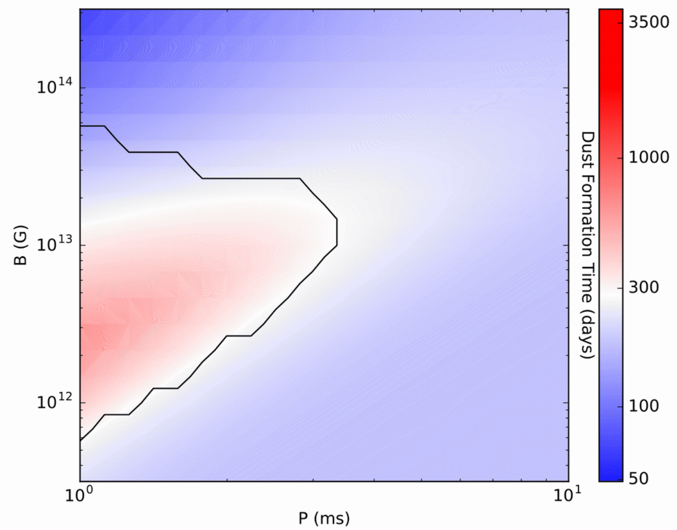
Increase Mass

B15-1

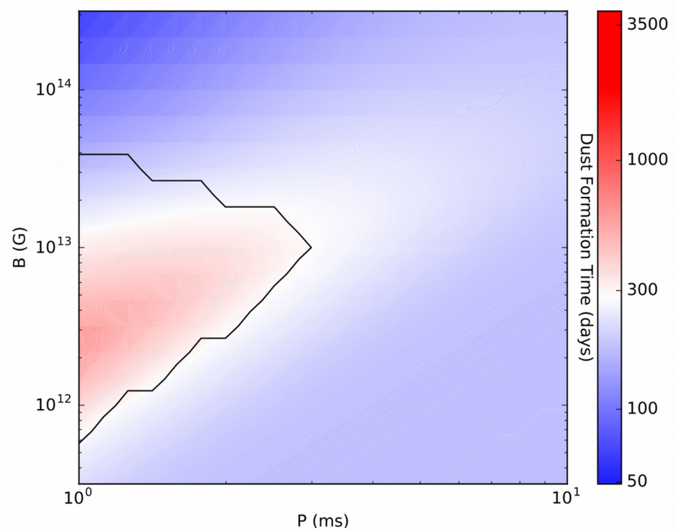


Formation Timescale (C5-1 and C15-1)

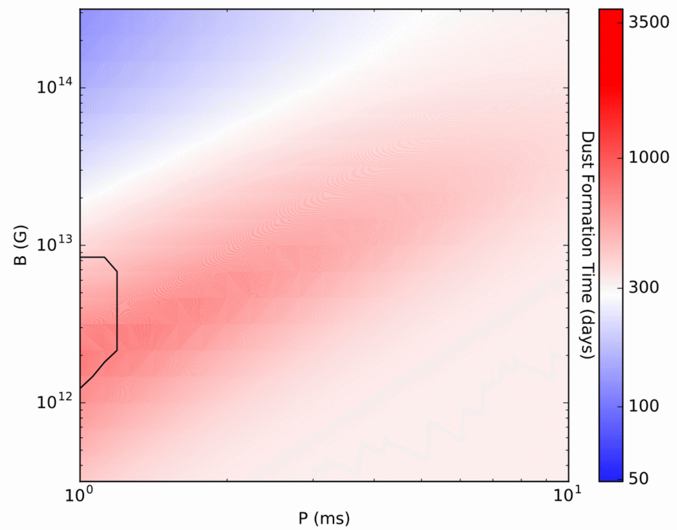
C Dust



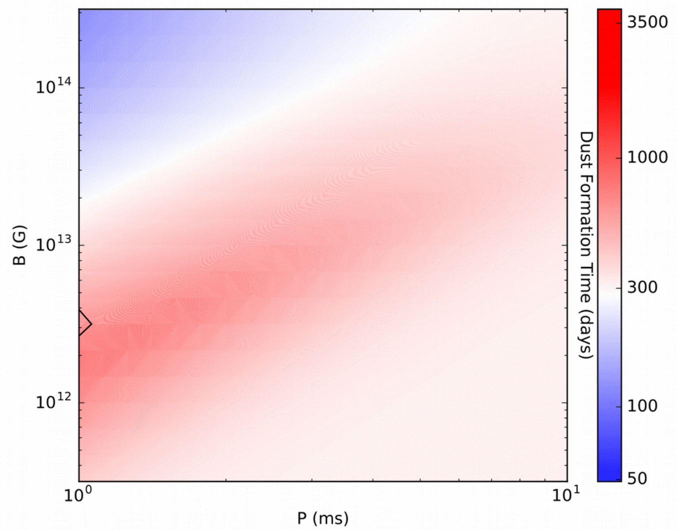
5 $M_\odot$



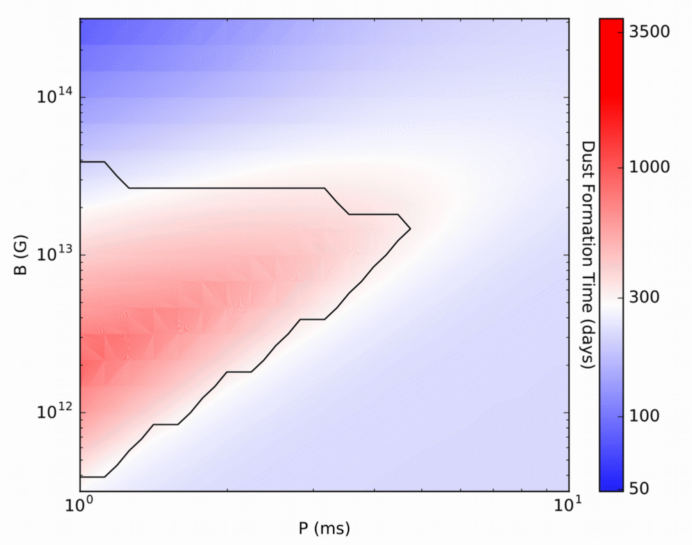
Change Composition B → C

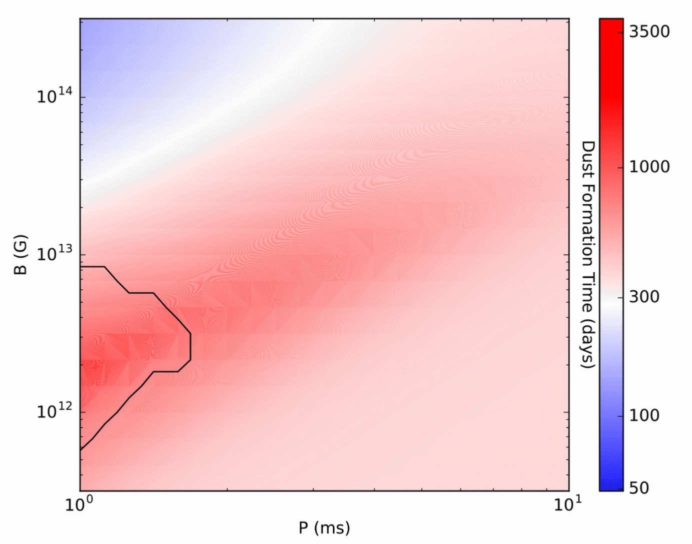


15 $M_\odot$



Formation Timescale (C5-1 and C15-1)



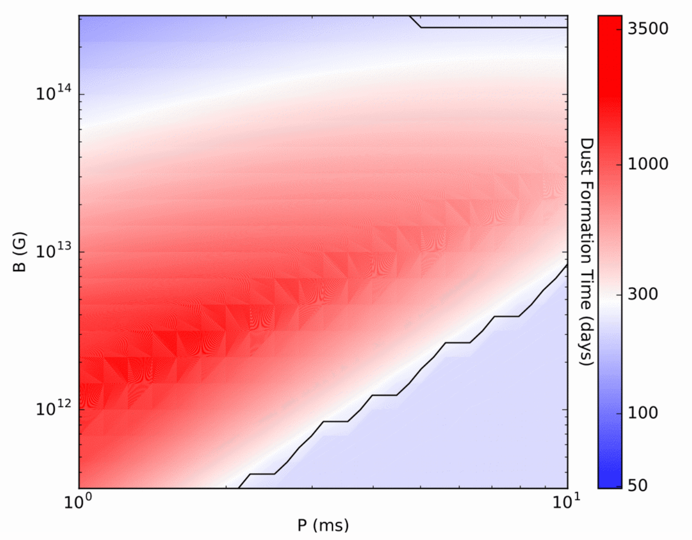


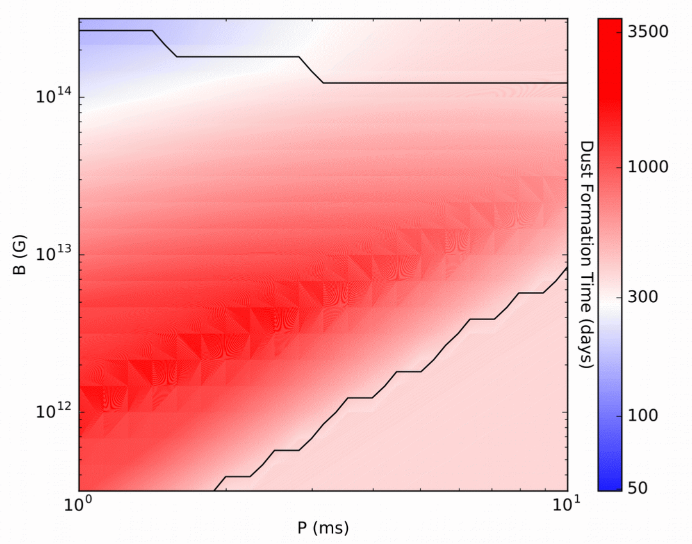
$MgSiO_3$/
MgO Dust

5 $M_\odot$

Change
Composition
B → C

15 $M_\odot$



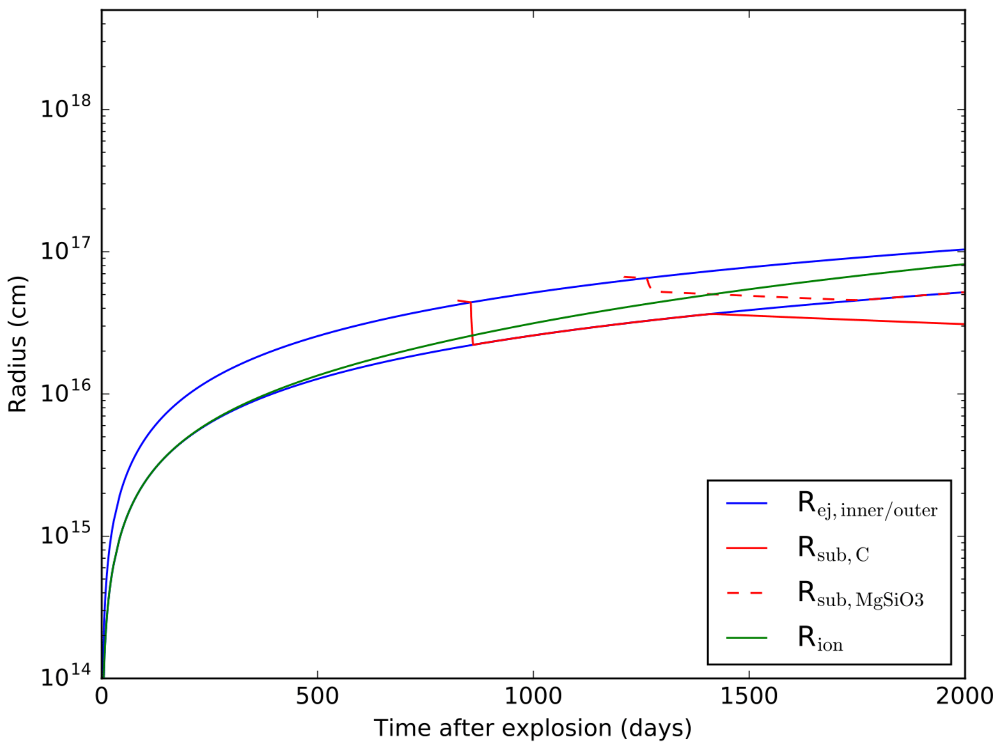


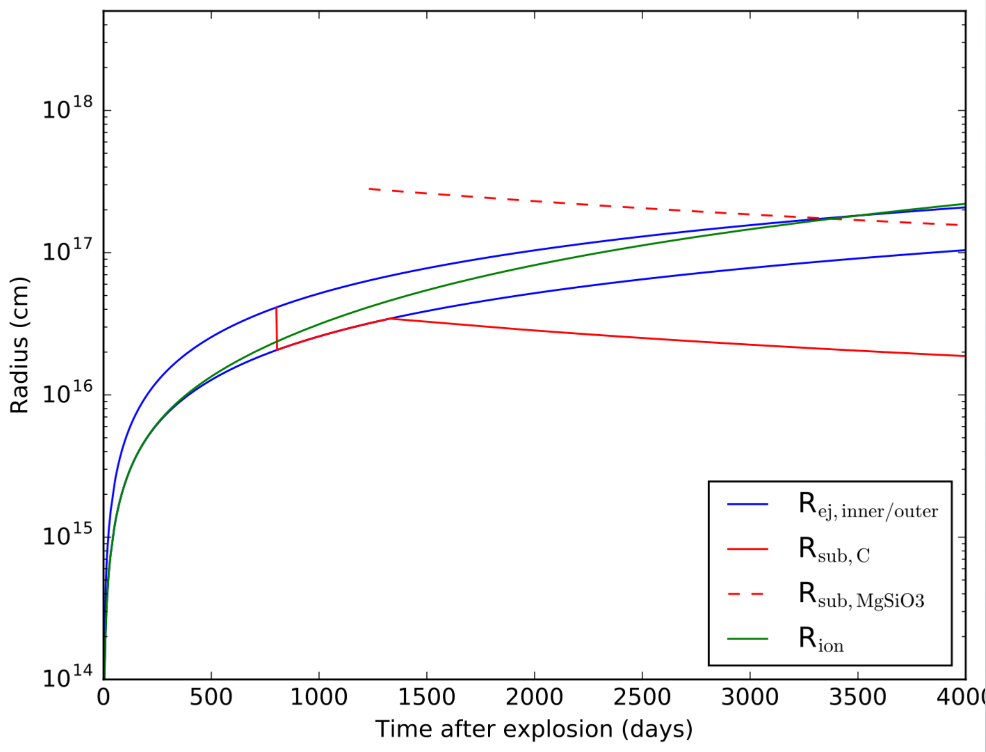
Radius Evolution (15 $M_\odot$)

B = 2 X 10^{12} G, P = 1 ms

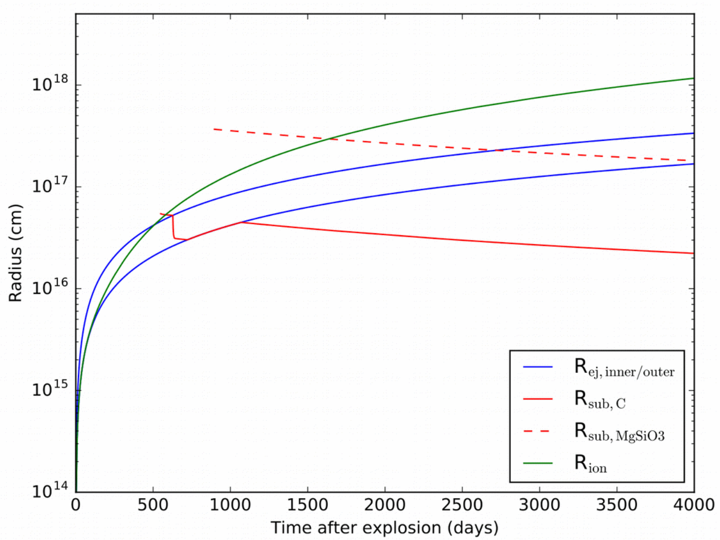
B composition

C composition



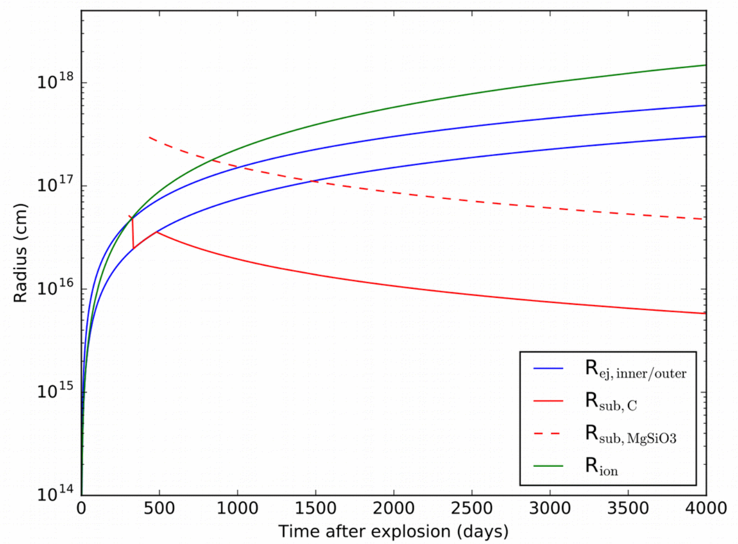


Radius Evolution (5 $M_\odot$)



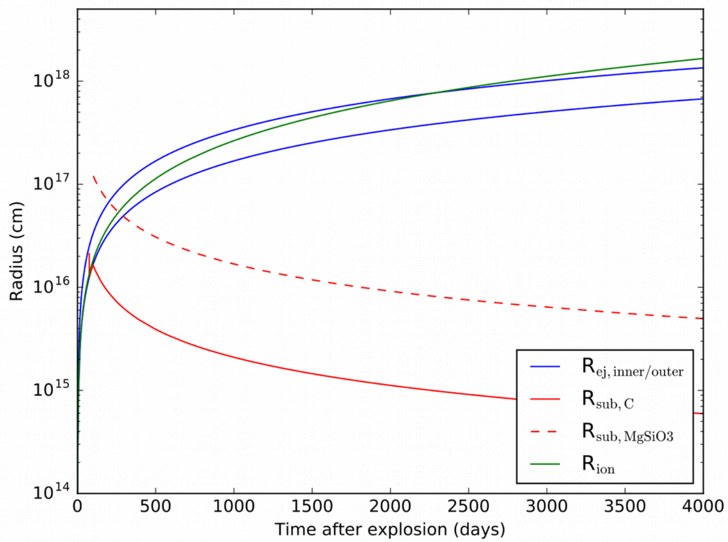
B composition, P = 1 ms

B = 1 X 10^{13} G



B = 2 X 10^{12} G

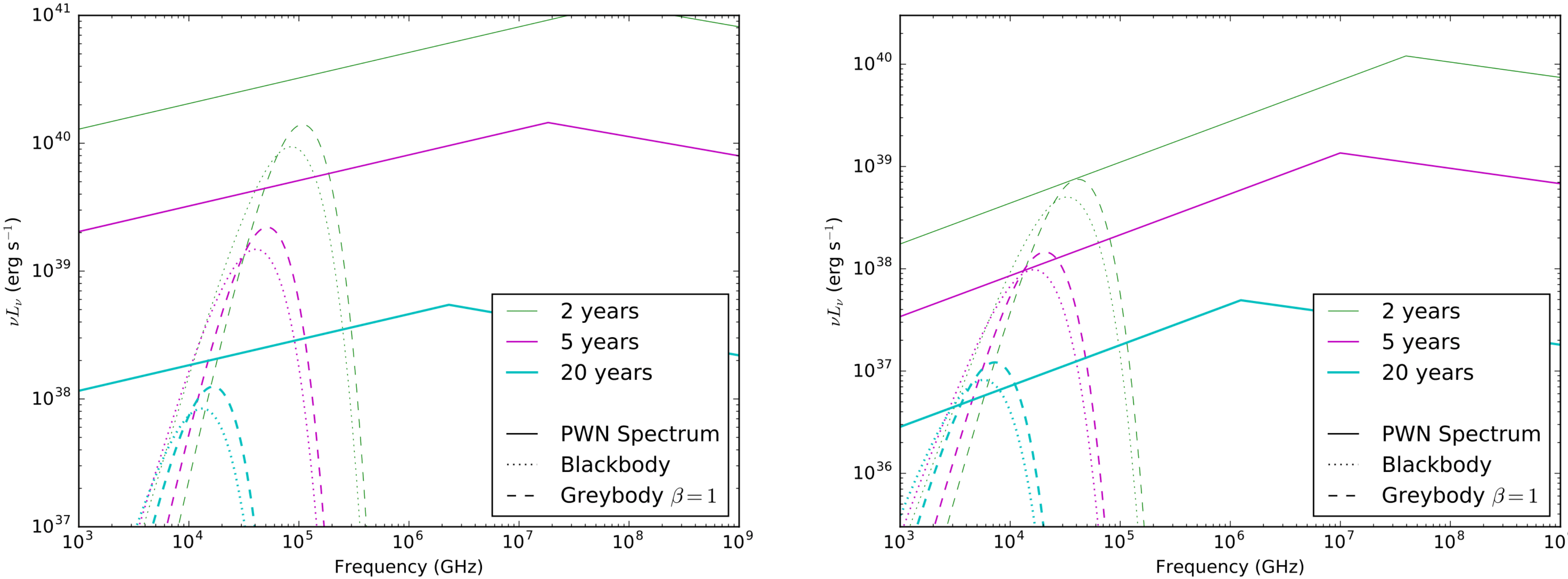
B = 1 X 10^{14} G



Dust Emission

B5-1

q_1 = 1.8 q_1 = 1.6



Summary

- Calculated dust formation for multiple ejecta compositions and pulsar parameters
- Formation timescale can vary from 50-4000 days, be delayed by sublimation or accelerated by fast ejecta
- Ionization barely effects dust in heavy ejecta, but can breakout of lighter ejecta
- Emission is sub-dominant to flat PWN spectrum, comparable to a less flat spectrum
- Dust size distribution still to be investigated