Toward nebular spectral modeling of magnetar-powered supernovae

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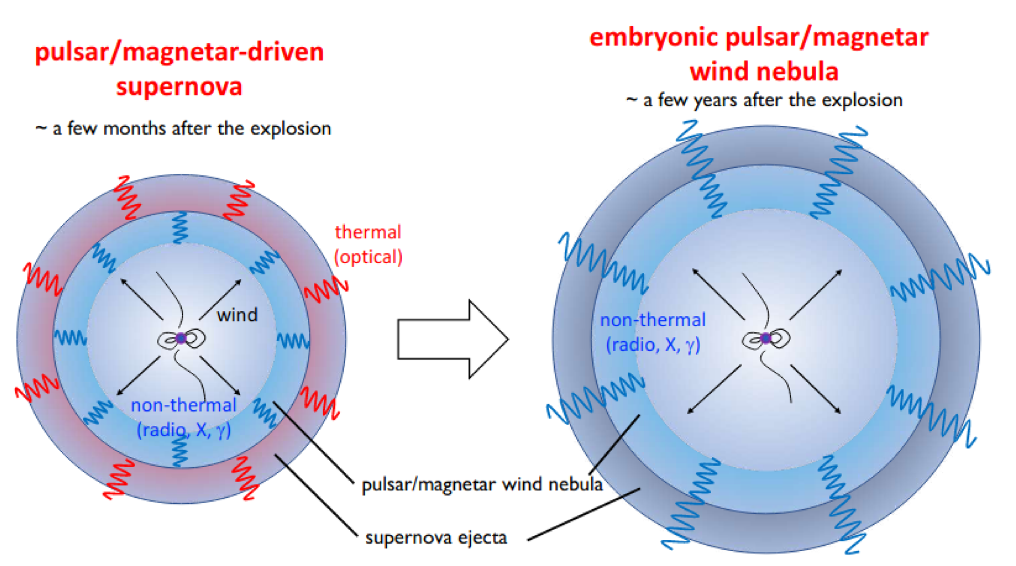
Many energetic supernovae (SNe) are thought to be powered by the rotational energy of a highly magnetized, rapidly rotating neutron star. The emission from the associated luminous pulsar wind nebula (PWN) can photoionize the SN ejecta, leading to a nebular spectrum of the ejecta with signatures that might reveal the PWN. SN 2012au is hypothesized to be one such SN.

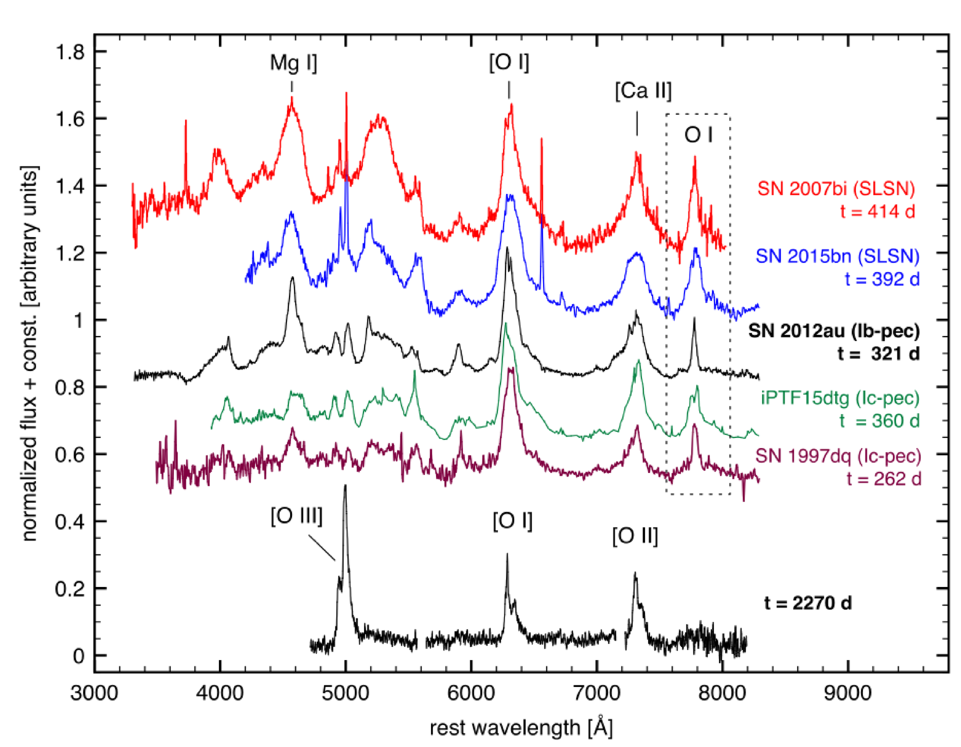
We present a suite of late-time (1-6 yr) spectral simulations of SN ejecta powered by an inner PWN. Over a large grid of one-zone models, we study the behavior of the physical state and line emission of the SN as the PWN luminosity, the injected spectral energy distribution (SED) temperature, the ejecta mass, and the composition vary. Certain models can reproduce the oxygen line luminosities of SN 2012au reasonably well at individual epochs, but we find no model that fits over the whole time evolution. This is likely due to uncertainties and simplifications in the model setup. Using our derived constraints from the nebular phase, we predict that the magnetar powering SN 2012au had an initial rotation period ~15 ms, and should be a strong radio source for decades.

Background



In the pulsar-driven model, the spin-down energy from the pulsar is injected into the ejecta via synchrotron radiation in the PWN and thermalized in the first few months post explosion (shown schematically above), but can pass through or affect the ionization structure of the ejecta at late times, leading to difference in the nebular spectrum.

SN2012au was inferred to have a PWN based on its slowly declining lte-time light curve and the spectra taken at 1 year and 6 years (Milisavljevic+ 2018, shown below). The high luminosity of the [O III] line, combined with the lack of OI emission, imply a photoionizing source at the centre of the expanding ejecta.



Modeling Supernova Nebular Spectra

To perform the spectral synthesis simulations, we used a modified version of the SUpernova MOnte carlo code (SUMO, Jerkstrand+ 2011). The code iterates between solving several aspects of the supernova system:

NLTE Statistical Equilibrium
22 of 28 elements from H to Ni, 4 ionization stages, ~100 excitation states each

Distribution of Compton Electrons
Spencer-Fano equation

Temperature
Heating = Cooling

Radiative Transfer
Monte Carlo method
Sobolev approximation
Injected photons from the engine
300 000 atomic lines, 3000 bound-free continua, free-free, electron scattering

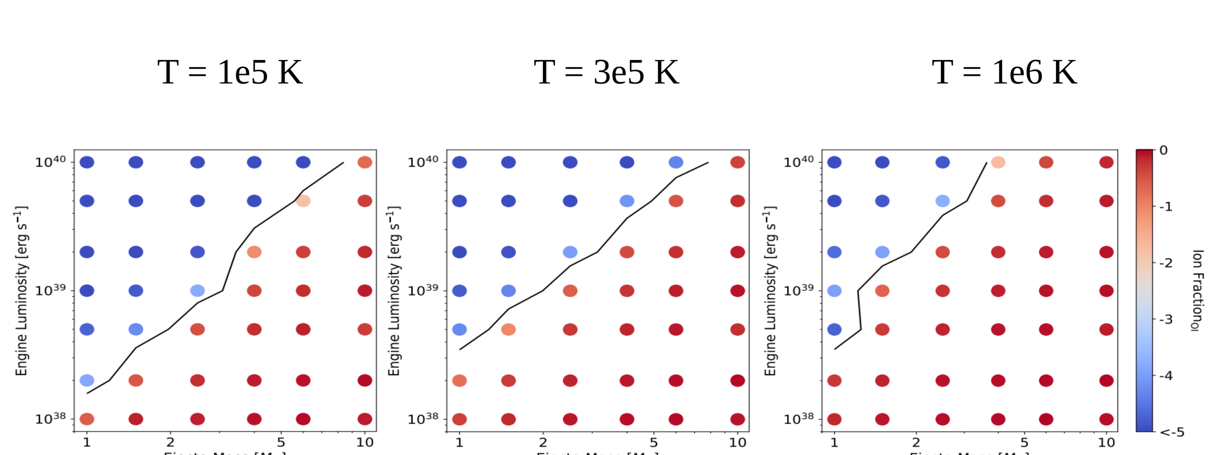
In our model, we use a pure oxygen ejecta expanding homologously between 2000-3000 km/s. The density profile is constant, with no clumping, and the treatment of the ejecta is as a single zone.

We treat the PWN spectrum as a blackbody parameterized with a temperature T and luminosity L. We vary these, as well as the ejecta mass, to find their effects on physical properties such as ionization fraction, ejecta temperature, and electron fraction; as well as the line luminosities for the O I, [O I], [O II], and [O III] emission lines and how they compare to the observed luminosities of SN2012au.

These are some caveats in our approach. We do not currently treat inner-shell ionizations at all, due to the code not currently calculating the Auger process or x-ray fluourescence. As such, we avoid the injection of x-ray or higher energy photons from the PWN, which limits the kinds of PWN spectra we can input. Also, the single zone, 1D, constant density treatment may not be correct if ionizing photons cannot penetrate the entire ejecta, and ignores clumping and mixing due to hydrodynamic instabilities (Suzuki and Maeda 2021).

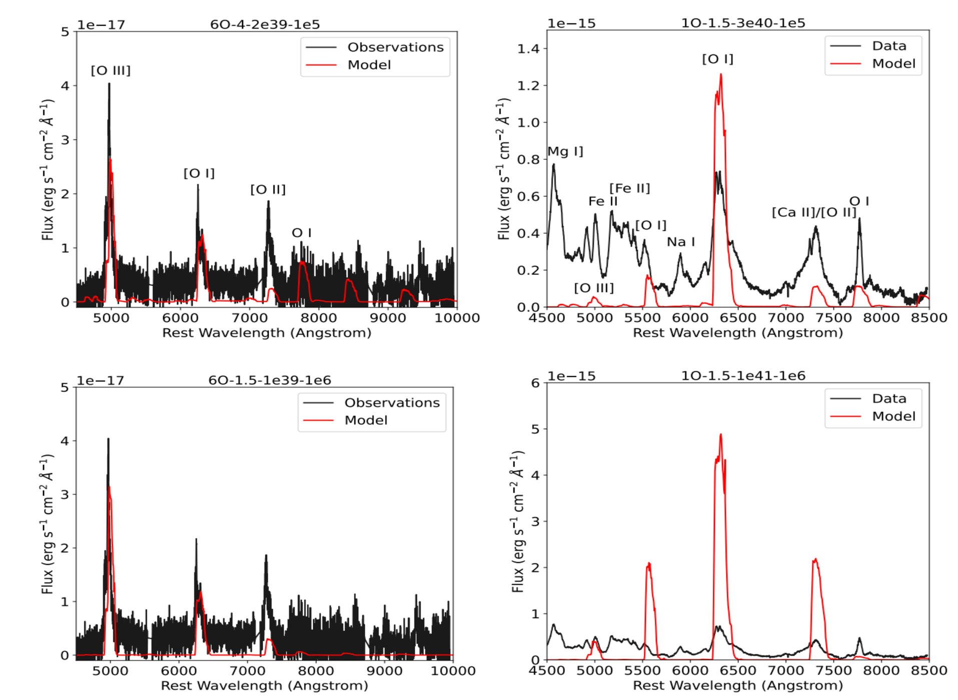
Spectral Models

We first ran simulations at 6 years with M = 1 - 10 $M_\odot$, L = 1e38 - 1e40 ergs, and T = 1e5 – 1e6 K for a pure oxygen composition. Here I show the ionization state of [O I] for each model. We find a sharp line in parameter place between mostly neutral and mostly ionized due to runaway ionization. This can also happen with [O II] in extreme circumstances.

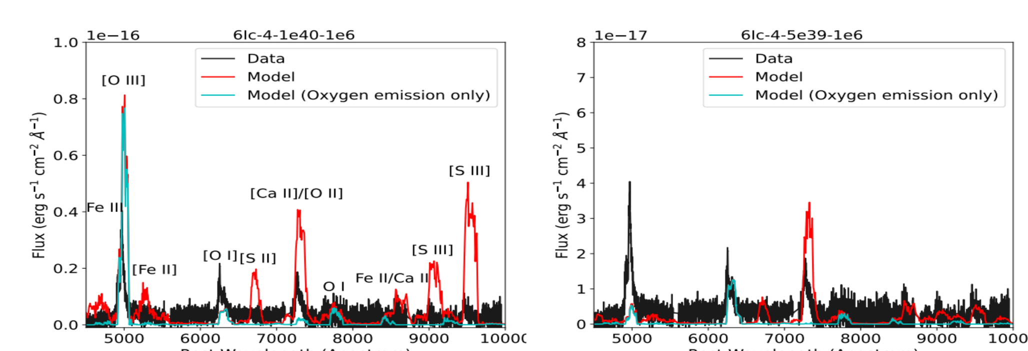


With pure oxygen ejecta at 6 years, a few of the models can reproduce the observations. Two models shown below fit well but underproduce [O II], while others that resembled the observations [O I] > [O III], or O I more luminous than the background signal.

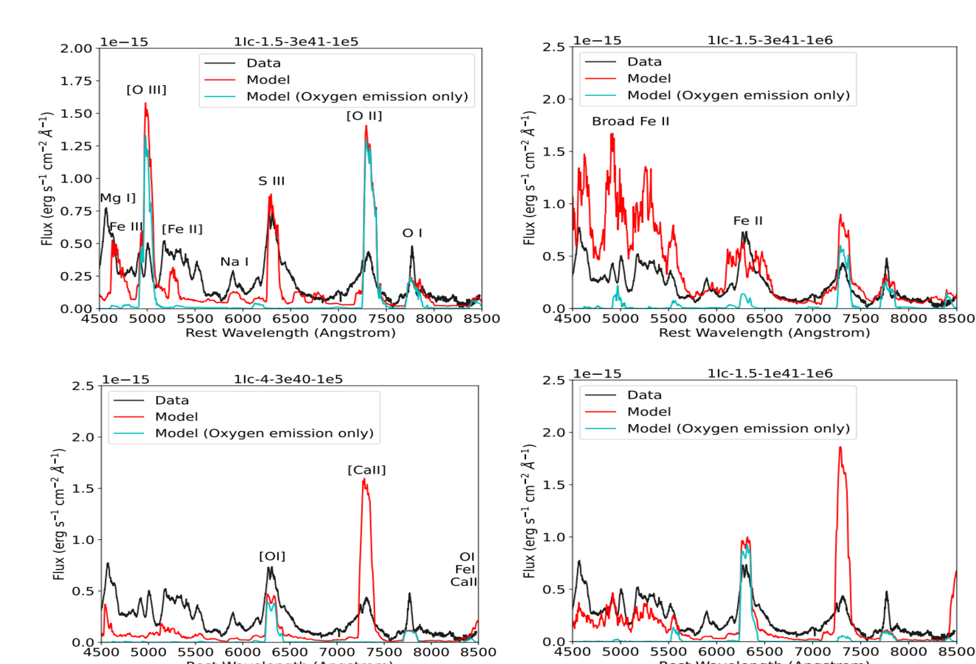
At 1 year, many spectra have [O II], [O III], and [O I] 5577 lines that are much stronger than observed. The only model spectrum close to observations has low temperature and luminosity, which is unphysical given the expected evolution of the magnetar.



With a realistic but fully mixed composition at 6 years, we require a much stronger PWN to reproduce similar line luminosities. These model are cooled strongly in IR, particularly by Ne II, and do not produce strong [O II]. None of the models reproduce observations, likely implying that O zones are not mixed with other elements (S, Ca, Fe) in the supernova.

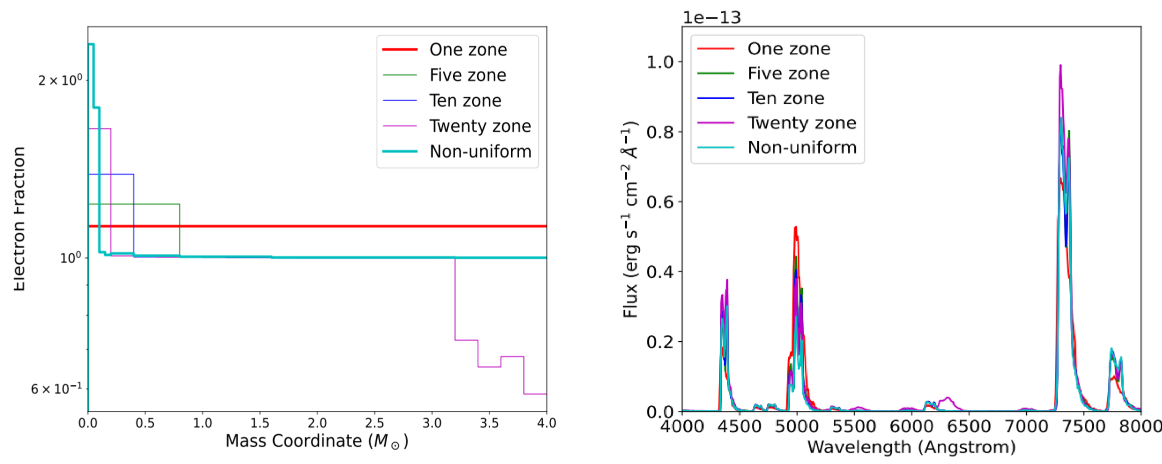


With a realistic but fully mixed composition at 1 years, we can produce strong Ca II and [O II] lines, especially at higher L, but some models can fit the observed [O I] and O I lines. Models predict Fe I/Fe II emission at lower wavelengths and strong emission in the NIR from Ca II, Fe I, and O I.



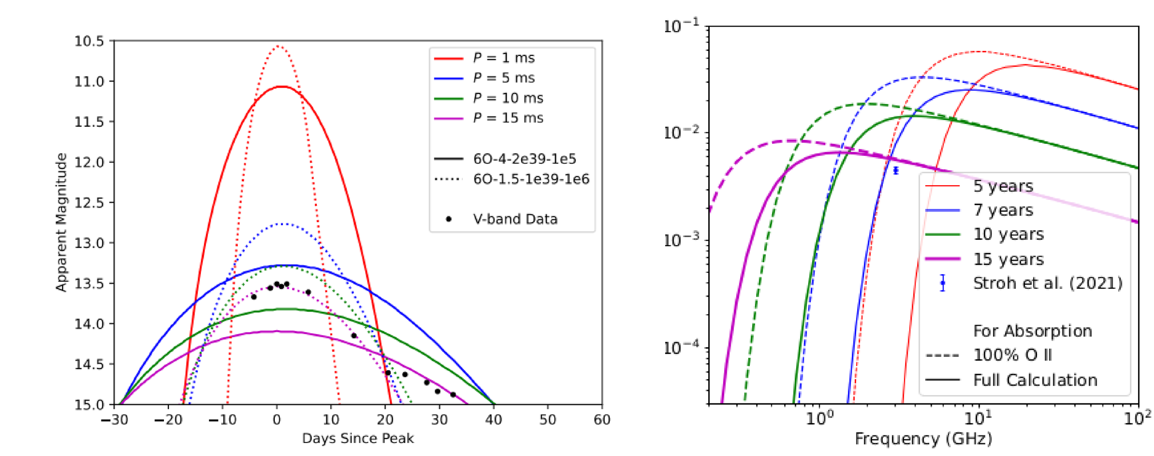
Discussion

We tested whether the emission changes in mutlzone versus one-zone models. In order to fully resolve the highly ionized inner region, we need a resolution of 0.1 $M_\odot$. This material is doubly or triply ionized, while the rest of the ejecta is dominated by O II. The temperature of this region is also higher than the surrounding ejecta by around 30%. The line luminosities of [O I] and [O II] are only weakly affected by the number of zones, while the luminosities of [O III] decrease by about a factor of two as the resolution of the inner zone increases.



We use the two best fitting spectral models from the pure oxygen composition at six years and plot the light curves resulting from those parameters and a number of initial pulsar spin periods. Around light curve peak, the best fit light curve has P = 15 ms, B = 4 x 10^{14} G, and M = 1.5 $M_\odot$.

Using these parameters and the SED inferred from the spectral models, we calculate the expected radio spectra for 5-15 years post explosion. The electron Lorentz factor is simlar to that of Galactic PWNe. This model predicts bright long-lasting emission with a free-free absorption break that decreases in frequency through time. This emission is consistent with observations and should be detectable by instruments such as VLA for decades.



Summary

We present a grid of late time (1-6 yr) spectral simulations of supernova ejecta powered by an inner PWN. We studied the behaviour of the physical state of the ejecta and line emission as PWN luminosity, PWN SED, and ejecta mass vary. We compare these results to SN 2012au, a candidate PWN-powered supernova.

We find several models the can reproduce the emission at 6 years, but none at 1 year. We take the parameters from models that can reproduce spectroscopic observations and find they can also reproduce the supernova light curve and radio emission, leading to a self-consistent picture of the supernova.