論文の内容の要旨

Multiwavelength Signals From Pulsar-Driven Supernovae
(パルサー駆動超新星からの多波長シグナル)

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The combination of extreme gravity, magnetism, and density make neutron stars a unique laboratory to probe theories like general relativity, quantum electrodynamics, and nuclear physics, so it is important to understand their formation, life cycle, and diversity. Yet, the youngest pulsar astronomers know about is the Kes 75 pulsar, which is around 700 years old. A central engine, like a fast spinning newborn pulsar or a black hole accretion disk, is thought to power many transients across the electromagnetic spectrum, including superluminous supernovae (SLSNe), hypernovae (HNe), and gamma-ray bursts (GRBs). We aim to elucidate the connection between pulsars and transients by predicting the detectability of multiple types of non-thermal signals unique to the pulsar engine and doing follow-up observations on promising candidates to verify or refute these predictions and further our understanding of both compact objects and the luminous transients they may cause. We also want to detect and study newborn pulsars, only a few years after their birth, as new insights in nuclear physics, condensed matter, plasma physics, quantum mechanics, and general relativity could come from identifying, modelling, and observing nascent neutron stars.

We first overview the history and significant discoveries in supernova and neutron star astronomy, starting from the first historical records of supernovae all the way to modern transient surveys. We then overview the process of core-collapse – which causes the shockwave that eventually becomes a supernova – and the dynamics of the supernova remnant (SNR). We then overview neutron stars and pulsars – specifically, the standard dipole formula for the spin-down of a rotating magnetized neutron star, the structure of and emission from the pulsar wind nebula (PWN), and a type of neutron star with its emission powered by the decay of an extremely high magnetic field – these are known as magnetars. We then introduce the main model we study in this work, the pulsar-driven model, which involves energetic transients being powered by the early emission from the PWN of a rapidly-rotating pulsar with a magnetic field between 10^{13}-10^{15}G. We overview SLSNe, HNe, and GRBs, the history of discovery for them, and their unique properties – we also introduce Fast Radio Bursts (FRBs), which are hypothesized to originate from similar pulsars on timescales of ~ 100 years post-explosion, and should thus be associated with the remnants of these explosions. We then focus on SLSNe-I, and explain other models that also can also explain the light curves from these events – an ejecta interaction with the surrounding circumstellar medium, a pair- or pulsational pair-instability supernova, or the fallback onto a central neutron star or black hole.

Quasi-thermal optical emission near the supernova peak can not differentiate a central pulsar from other possible engines. Murase et al. (2016) proposed that radio/submillimetre emission from non-thermal positron-electron pairs in the newborn PWN can be used to identify and characterize pulsars in the supernovae they power. We present our models for SLSNe-I early optical quasi-thermal emission using a pulsar engine, and fit the emission of six bright newborn SLSN-I remnants, obtaining parameter values for the pulsar rotation period, the pulsar magnetic field, and the ejecta mass. We obtain multiple parameter sets due to degeneracy in the parameters, so we take the slowest (P_{max}) and fastest (P_{min}) rotating neutron stars that are physical and fit the optical data as the extreme cases. We then present our model for calculating late-time broadband non-thermal emission, which includes synchrotron radiation, inverse Compton scattering, pair cascades, and multiple types of attenuation in both the PWN and ejecta. We use this model and the parameters derived with the optical model to calculate the expected radio/submillimetre light curves for those six SLSNe-I. We find that the Atacama Large Millimeter/submillimetre Array (ALMA) or NOrthern Extended Millimeter Array (NOEMA) can detect the submillimetre PWN emission from most of them in a few years after the

explosion, while the Very Large Array (VLA) can detect the radio PWN emission from a few of them in a few decades. Follow-up observations could help solve the parameter degeneracy problem in the pulsar-powered SN model and could give clues about young neutron stars scenarios for SLSNe-I and Fast Radio Bursts (FRBs).

We present our VLA observations of ten older SLSNe-I at 3 GHz, trying to look for the above-mentioned non-thermal emission. We perform the observations with 5 millisecond resolution so we can also search the supernova remnants for FRBs. We first overview the hardware and software used in these observations and analysis, the VLA interferometer, the *realfast* pipeline that searches the data for FRBs, and the CASA analysis and reduction toolkit. We then overview our observations, including both the fast-resolved FRB search and the deep imaging search. The fast-resolved search did not detect anything, but the deep imaging search did detect emission from PTF10hgi with a luminosity of 1.2 x 10^{28} erg s^{-1} (47 $\pm$ 14 μJy). This detection, along with the recent 6 GHz detection of PTF10hgi by Eftekhari et al. (2019), supports the interpretation that this SLSN-I is powered by a young, fast-spinning (~ ms spin period) magnetar with ~ 15 $M_\odot$ of partially ionized ejecta. Our observations are broadly consistent with SLSNe-I being powered by pulsars with fast spin periods, although our non-detections suggest most require more free-free absorption than is inferred for PTF10hgi. With regards to the non-detections, our current model (which contains many assumptions about the microphysics of the PWN) is ruled out for one of the supernovae, constrains the pulsar spin period for three others, constrains the ejecta ionization state for four others, and does not constrain one at all. We predict that radio observations in the near future or at higher frequencies should be able to detect these systems and constrain properties of the young pulsars and their birth environments.

We present a larger, deeper sample of observations at both radio (6 GHz) and submillimetre (100 GHz) frequencies to try to detect additional sources and help further constrain the model. We use CASA again for analysis and reduction, so we only need to introduce ALMA. We then detail our observations and sample of 28 SLSNe-I, before introducing the *MOSFiT* (the Modular Open-Source Fitter for Transients), which we used to fit the multiband optical data from our sample. *MOSFiT* uses a Markov-Chain Monte Carlo (MCMC) algorithm to determine best-fit parameters using Bayesian inference, but uses a simplified pulsar-driven model compared to the one used earlier, so we adapt the dynamics of our previous broadband emission model to be consistent with *MOSFiT*. There was no emission detected from any of the sources, but these observations exclude the model for seven sources and constrain ten others. Further radio observations of PTF10hgi (Mondal et al. 2020) do broadly support the pulsar-driven model, although a specific parameter set that fits all available data has not yet been found. These observations highlight the need for more sophisticated models and better methods for excluding regions of parameter space, and the underlying difficulty of trying to exclude a scenario with many free parameters.

After discussing the direct detectability of PWN emission in previous chapters, we introduce a method of detecting pulsar wind nebulae through their effect of the surrounding ejecta via the detection of reprocessed PWN emission from dust grains in the supernova ejecta. Dust emission has been observed in many supernova remnants that also have a central neutron star, and we investigate the effect of their nebulae on dust formation and evolution in the supernova ejecta. We model dust formation using a steady-state model as formulated by Nozawa and Kozasa (2013), account for sublimation of the dust by non-thermal PW radiation using the formulation of Waxman and Draine (2000), account for ionization in the gaseous ejecta, and calculate thermal re-emission from the PWN-heated dust. We study the dependence of dust formation time and dust size on the properties of the ejecta and central pulsar and find that a pulsar can either accelerate or delay dust formation, with timescales of a few months to over 15 years, and reduce the average size of dust by a factor of ~ 10 or more compared to the non-pulsar case, down to our model minimum. We also find that infrared dust emission may be detectable in typical SLSNe-I out to ~ 100-1000 Mpc in 2-5 years after the explosion, although this depends sensitively on the spectral index of the nebula, which is still not well known. We also discuss implications on previous supernova observations, although most galactic supernovae are not expected to have their dust formation histories significantly impacted by their PWNe. There are a few caveats of this approach: the uncertainty in the PWN makes it unclear if most of the energy will be emitted in a band that can be absorbed by dust, our treatment of emissivities is approximate and may not be valid for smaller dust, multidimensional hydrodynamic instabilities can induce mixing in the ejecta, and some smaller assumptions may affect our results – we discuss the implications for all model caveats.

Finally, we give concluding remarks on the outlook of the SLSN and pulsar-driven SN community, summarizing the implications of this research and discuss interesting possibilities for future studies. The results for the pulsar-driven model are inconclusive so far, with a few promising sources and a few troubling non-detections. The work done so far is an important foundation for our understanding of these transients, but much work remains to be done to uncover their true nature.