論文の内容の要旨

論文題目 Supernovae Interacting with Circumstellar Media (星周物質と相互作用する超新星)

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Core-collapse supernovae are explosions of massive stars. Massive stars lose their mass during their evolution in many ways and core-collapse supernovae always occur within circumstellar media created by their progenitors. We study signatures of circumstellar media which appear in supernovae due to the interaction between supernova ejecta and circumstellar media. Our study reveals mass loss of supernova progenitors immediately prior to their explosions. We especially focus on supernovae whose main radiation energy source is kinetic energy of supernova ejecta. If circumstellar media of supernovae are dense enough, supernova ejecta is decelerated by the interaction and the kinetic energy of the supernova ejecta is eventually released as radiation. The efficient conversion from kinetic energy to radiation energy can make supernovae bright.

We develop theoretical formalisms to study the light curves of such interacting supernovae at first. We derive an analytical bolometric light curve model under the assumption that circumstellar media are optically thin. When circumstellar media are optically thick, we need to model light curves numerically. However, if the optical depth of a circumstellar medium is sufficiently high and the shock breakout occurs within the circumstellar medium, we find that the rising time of the light curve and the shock propagation timescale in the circumstellar medium can be estimated analytically. These timescales can be used to infer the properties of circumstellar media in which the shock breakout occurs.

We apply our analytic light curve model to observed Type IIn supernova light curves. Type IIn supernovae are supernovae which show clear signatures of the interaction in their spectra and they are presumed to be mainly powered by the interaction. By fitting the observed light curves by our analytic model, the properties of the circumstellar media of several Type IIn supernova progenitors are estimated. We find that the density structures of them are likely to deviate slightly from the density structures expected from the steady mass loss and Type IIn supernova progenitors generally experience non-steady mass loss shortly before their explosions. Especially, we find that Type IIn supernova progenitors may tend to increase their mass-loss rates as they get closer to the time of their explosions. In addition, the mass-loss rates estimated are found to be more than 0.001 solar mass per year. No supernova progenitors are predicted to have such high mass-loss rates shortly before thieir explosions by the current stellar evolution theories and our results clearly challenge our understanding of mass loss from massive stars.

Superluminous supernovae are a new kind of supernovae whose existence is recently recognized. Their peak luminosities are brighter than -21 magnitude in optical. Most of them are Type IIn supernovae and they are suggested to become superluminous because of the interaction between supernova ejecta and circumstellar media. To explain the huge luminosities of superluminous supernovae, their circumstellar media need to be very dense and the shock breakout is presumed to occur within the circumstellar media. By modeling the light curve numerically, we find that the observed properties of the best observed superluminous supernova 2006gy (Type IIn) can be actually explained by the shock breakout model we developed. Our results indicate that the progenitor of supernova 2006gy underwent non-steady mass loss with the rate exceeding 0.1 solar mass per year in a few decades before the explosion. No current stellar evolution models can explain the estimated mass loss. There also exist superluminous supernovae whose spectral type is not Type IIn and their huge luminosities are not necessarily from the interaction. However, we find that the lack of the Type IIn features in their spectra can be explained by our shock breakout model and they likely get bright due to the interaction as well. Especially, the existence of the two spectral types (Type IIn and Type IIL) in hydrogen-rich superluminous supernovae and a short-term luminosity decline observed between the precursor and the main light curve of hydrogen-poor superluminous supernova 2006oz are naturally expected from the shock breakout model.

So far, we have discussed the mass-loss properties of the observed supernovae which show the signatures of the interaction and found that their mass-loss rates are much higher than those predicted by the current stellar evolution theories. However, there do exist some theoretical supernova progenitor models whose mass-loss rates are enhanced shortly before their explosions, namely, super-asymptotic-giant-branch stars, massive red supergiants, and luminous blue variables. We discuss the expected observational signatures of these theoretical supernova progenitors with the mass-loss enhancement. We obtain light curves from the explosions of electron-capture supernovae theoretically suggested to explode within super-asymptotic-giant-branch winds. Some observed supernovae are suggested to come from super-asymptotic-giant-branch stars but we find that their light curves are inconsistent with the light curves obtained by the super-asymptotic-giant-branch star model from the current stellar evolution theories. Massive red supergiants are suggested to have enhanced mass loss shortly before their explosions and supernovae from them are found to have a long ultraviolet-bright phase and possible spectral transition from Type IIn to Type II. Supernovae with these features exist (2009kf, 1987C, and 2007pk) and they are likely from massive red supergiants. The mass-loss rates of recently reported luminous blue variable supernova progenitors are found to be too low to affect optical supernova light curves but their episodic mass-loss enhancement due to the bistability can explain episodic modulations observed in some supernova radio light curves.

Finally, we investigate supernova remnants of supernovae interacting with dense circumstellar media. We suggest that recombining supernova remnants whose existence is recently confirmed are from supernovae interacting with dense circumstellar media. We find that the progenitors of recombining supernova remnants should be mostly massive red supergiants and Type IIn supernova progenitors.