C207; Project Set #3

due 3/07/2013

Interactions of a Nearby Supernova

Figure 1: Image of SN 2011fe in the Pinwheel galaxy (Nuget et. al (2011))

One of the more exciting astronomical events of 2011 was the discovery of a very nearby supernova in M101 (the Pinwheel galaxy) only ~ 7 Mpc away. The event, SN 2011fe, was a Type Ia supernova, believed to be the explosion of a white dwarf. Visible with a good pair of binoculars, it generated quite a bit of public interest.

The progenitors of Type Ia supernovae are still a matter of debate. In one popular model (the single degenerate scenario) the progenitor is a carbon oxygen white dwarf star which accretes material from a companion star, reaches a critical mass, and explodes. In another model (the double degenerate scenario) the explosion is triggered by the merger of two white dwarfs. One way of potentially distinguishing the scenarios is to study the circumstellar medium (CSM) surrounding the system. In the double degenerate case, the CSM density should be rather low. In the single degenerate case, on the other hand, the donor star (e.g., a main sequence star or a red giant) will likely lose mass through a wind. Assuming a constant mass loss rate, the density surrounding the explosion would be

$$\rho_{\rm csm}(r) = \frac{\dot{M}_{\rm w}}{4\pi v_w r^2} \tag{1}$$

where $\dot{M}_{\rm w}$ is the mass loss rate, and v_w the wind velocity, which we expect to be comparable to the escape velocity from the star. If this CSM exists, we may be able to see emission when the supernova ejecta crashes into it.

Horesh et al. 2012 observed SN 2011fe with the Chandra satellite telescope, but failed to detect any x-ray emission. The Chandra observations taken ~ 4 days after the explosion put an upper limit on the x-ray luminosity[1] of $L_x < 4.4 \times 10^{36}$ ergs s^{-1}. We can use a simple model of the x-ray emission to derive constraints on the CSM density. When the supernova impacts the CSM, it drives a shock through it, heating and compressing the gas. For a strong shock, the thermal energy density of the shocked gas is comparable to incoming kinetic energy density. In particular, the shock jump conditions give for an ideal gas

$$nkT = \frac{3}{16}\rho_{\rm csm} v_{\rm sh}^2 \tag{2}$$

where $v_{\rm sh}$ is the shock velocity, which we will take to be a constant. The shock compression also increases the density of the CSM by a factor of 4.

[1] They have apparently done a bolometric correction by extrapolating the spectrum outside the observed wavelength bands assuming an optically thin free-free spectrum, so that the quoted luminosity is the total free-free emission.

We will imagine this hot, shocked CSM to lie in a shell with an inner radius $r_{\rm in} \approx v_{\rm sn} t$ where $v_{\rm sn} \approx 30,000$ km s^{-1} is a typical velocity for the fastest moving supernova ejecta, and t is the time since explosion. The outer radius of the shell is $r_{\rm out} \approx v_{\rm sh} t$ where the shock moves just a little faster than the supernova ejecta, $v_{\rm sh} \approx 1.1\ v_{\rm sn}$.

a) Estimate the temperature of the shocked CSM. Assuming the radiation is due to the thermal free-free emission, what do you expect the spectrum to look like in the Chandra bands (0.1 - 10 keV)?

b) Assuming the shell is optically thin, integrate the free-free emission over the shell volume and derive an expression for the total thermal luminosity. Show that, under our assumptions, the thermal emission from interaction decreases with time as t^{-1}.

c) Using the Horesh et. al (2012) constraint at 4 days, and assuming a wind velocity of $v_w = 10^7$ cm s^{-1}, put an upper limit on the mass loss rate $\dot{M}_{\rm w}$ in units of solar masses per year.

d) We should make sure that the assumption of optically thin emission is reasonable. At what value of $\dot{M}_{\rm w}$ does the shell become optically thick to free-free self absorption at day 4 and a typical x-ray wavelength of 1 kev?

Comment: In addition to the shock propagating into the CSM, there will also be a reverse shock which propagates back into the supernova ejecta, slowing down and heating the ejecta. In typical cases, the shocked ejecta is denser than the shocked CSM, and thus emits more free-free radiation. In fact, the reverse shock emission can be a factor of ~ 30 greater. You can use this fact to place an even tighter constraint on the mass-loss rate.

Comment: In addition to the thermal electrons, a significant portion of the shock energy likely goes into accelerating non-thermal electrons. These electrons will produce synchrotron emission at radio wavelengths, as well as inverse compton emission at x-ray wavelengths. The constraints derived from analyzing these processes are significantly stronger than that of the thermal free-free emission.

Comment: The constraints on the CSM density from the SN 2011fe observations are able to rule out some progenitor systems, for example those where the companion is a highly evolved red giant which blows a strong wind ($\dot{M} > 10^{-5}\ M_\odot$ yr^{-1}). However it is still possible that the companion was a main sequence star with a lower

mass loss rate. Thus these observations can not definitively answer whether the progenitor was of the single degenerate or the double degenerate type.

Powering Radio Lobes

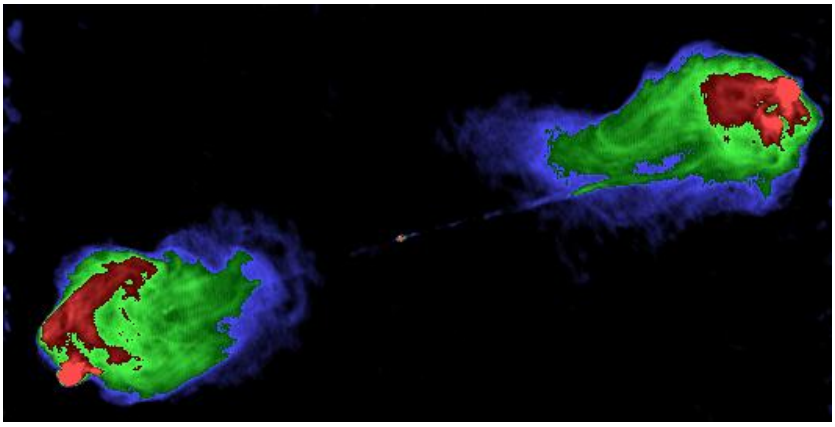

Figure 2: Radio image of Cygnus A, showing the extended lobes powered by narrow jets from the central super-massive black hole. The lobes are about 30 kpc in radius, and the emission is strongest at the front regions which are presumably interacting most strongly with the ambient medium

The galaxy Cygnus A is one of the most powerful radio sources in the sky. Striking radio images (figure 1) reveal a pair of immense lobes of emission, which sit about $\sim$ 100 kpc outside the central galaxy. It is thought that these lobes are powered by a super-massive black hole (SMBH) at the galactic center. The SMBH somehow produces narrow, bipolar, relativistic jets, which propagate to the outskirts of the galaxy, interact with the ambient medium, and form shocks. The radio luminosity is the result of synchrotron emission from relativistic electrons produced in those shocks.

Figure 3 shows the observed radio spectrum of Cyg A, which resembles what we might expect from synchrotron emission – broadband, roughly power-law, clearly non-thermal. The observed flux increases down to a frequency of at least 10 MHz, where the value is $F_\nu \approx 10^4$ Jy[2]. In this region, one can reasonably fit a power law to the spectrum and write the specific luminosity

$$L_\nu = 4\pi d^2 F_\nu = 5 \times 10^{36} \left(\frac{\nu}{10\ \mathrm{MHz}}\right)^{-0.8} \mathrm{ergs\ s^{-1}\ Hz^{-1}} \qquad (3)$$

where we have taken the distance to Cyg A to be $d \approx 230$ Mpc. Integrating equation 3 over the observed range $10^7 - 10^{11}$ Hz gives a luminosity of $L \sim 10^{45}$ ergs s^{-1} (about 1000 times the energy radiated by a supernova at peak).

[2] The Jansky, defined by 1 Jy $= 10^{-23}$ ergs s^{-1} Hz^{-1} cm^{-2} is the preferred unit of flux in radio astronomy.

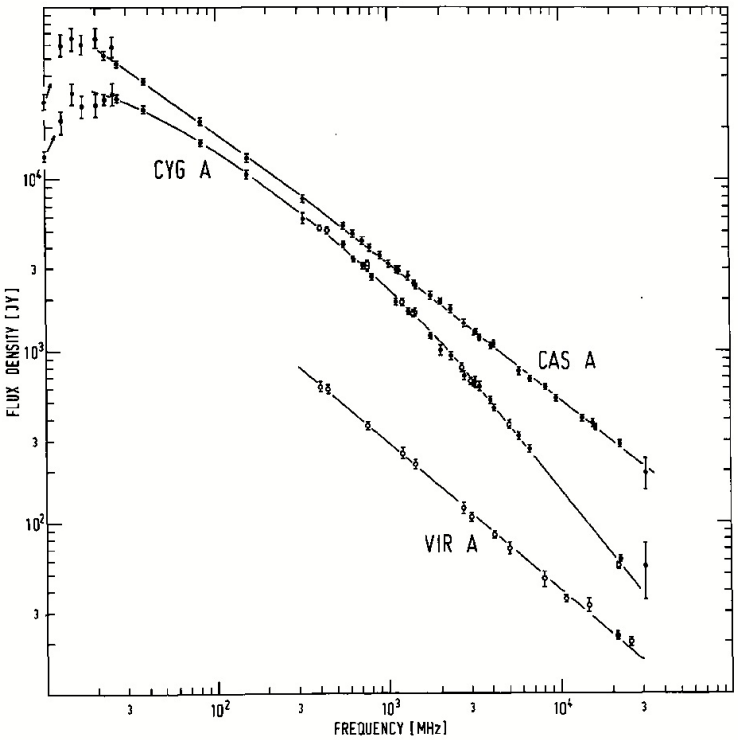

Figure 3: Radio spectrum of Cyg A (and other objects) from Baars et al (1977)

What are the energetics and magnetic field strengths involved in these luminous radio lobes, and can a SMBH really provide the necessary oomph? The total energy[3] in the lobes can be written

$$E = (u_e + u_B) \times 2V \tag{4}$$

where u_e, u_B, are the electron and magnetic field energy densities, respectively, and V is the volume of a lobe[4]. As it turns out, we do not have enough information to directly determine these energy densities, but we can follow the famous arguments of Geoffery Burbidge to derive a lower limit. The implied energies, we will find, are massive – the equivalent of a billion supernova explosions or more.

As usual, we'll take the electron number density to be described by a power law distribution in lorentz factor

$$n d\gamma = C\gamma^{-p} d\gamma \tag{5}$$

where C is some constant and the power-law cuts off at some lower value, γ_{min}.

a) Infer the value of p from the observations.

b) Integrate equation 5 to get an expression for the energy density of electrons, u_e in terms of C and γ_{min}.

[3] We are going to ignore the energy in protons, since there is no easy way to measure them directly. But presumably there is as much or more energy in protons than electrons.

[4] The lobes each have a radius of around 30 kpc. We have included a factor of 2 in the equation since there are two of them

What should we use for $\gamma_{\rm min}$ and C? It looks like the observed spectrum might be peaking at $\nu_m \approx 10$ MHz. We can therefore associate[5] 10 MHz with the critical frequency of electrons with lorentz factor $\gamma_{\rm min}$. To determine the constant C, we can use the observed specific luminosity at the frequency $\nu_m = 10$ MHz. From synchrotron theory we know that the specific luminosity (ergs s^{-1} Hz^{-1}) from a power law distribution of electrons is

$$L_\nu \approx \frac{2C}{3}\frac{u_B \sigma_t c}{\nu_{\rm cyc}}\left(\frac{\nu}{\nu_{\rm cyc}}\right)^{-(p-1)/2} \times V \tag{6}$$

[5] This may or may not be correct. The data is getting a little sketchy around 10 MHz – perhaps with better quality observations we would find that the power law extends below 10 MHz. It could also be that the turn over is real, but due to synchrotron self-absorption, not to the minimum lorentz factor. If ν_m is in fact smaller than 10 MHz, this would imply an even smaller $\gamma_{\rm min}$ and hence even more energy. Thus what follows is at least a lower limit to the energy.

c) Show that the energy density of electrons can be written

$$u_e = A\frac{L_m \nu_m^{1/2}}{V}B^{-3/2} \tag{7}$$

where L_m is the observed specific luminosity at ν_m, and A is some combination of numerical factors and fundamental constants.

To proceed, we need to know the magnetic field strength. Unfortunately, there is no easy way to measure this directly. What is typically done instead is to make a *minimum energy* argument. The magnetic energy density increases with B, whereas equation 7 shows that u_e grows as B *decreases.* Thus there must be some comprise value of B which minimizes the total energy. This value will at least give us a lower limit to the necessary energetics.

d) Show that the total energy is minimized when $u_B = 3/4 u_e$ – that is, when u_e and u_B are roughly equal. For this reason, the minimum energy argument is often also called an equipartition argument.

e) Adopting the equipartition argument above, what is (numerically) the magnetic field strength in the emitting regions? What is the minimum lorentz factor, $\gamma_{\rm min}$?

f) What is the total energy in the radio lobes? How does this compare to the typical energy of a supernova?

g) How much mass mass would a black hole have to eat in order to create this energy? Assume that the rest mass energy of the accreted material is processed into jet energy with 10% efficiency. Does the SMBH hypothesis hold together? – i.e., is your estimate for the swallowed mass consistent with SMBH masses?

Comment: We have provided no physical justification for why this system should generate magnetic fields with $u_B \approx u_e$. We have only

shown that equipartiation is the optimal configuration for radiating efficiently. However, if the magnetic field is produced by turbulent motions in the plasma, which also play a role in accelerating the high energy particles, perhaps there is some rationale for thinking that we may reach something close to equipartition. This conjecture can now be tested by detailed particle-in-cell simulations, which follow the motions of individual particles in a plasma while simultaneously solving Maxwell's equations to determine the fields they generate. In the absence of any better information, people often simply assume an equipartition B-field in order to carry out synchrotron analyses. Note that we have also neglected here the energy in relativistic protons, which could exceed that in electrons and magnetic fields.