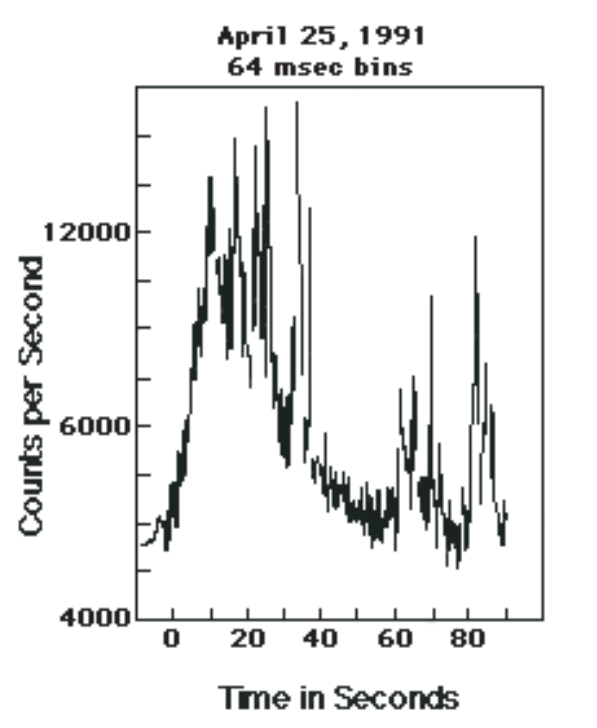
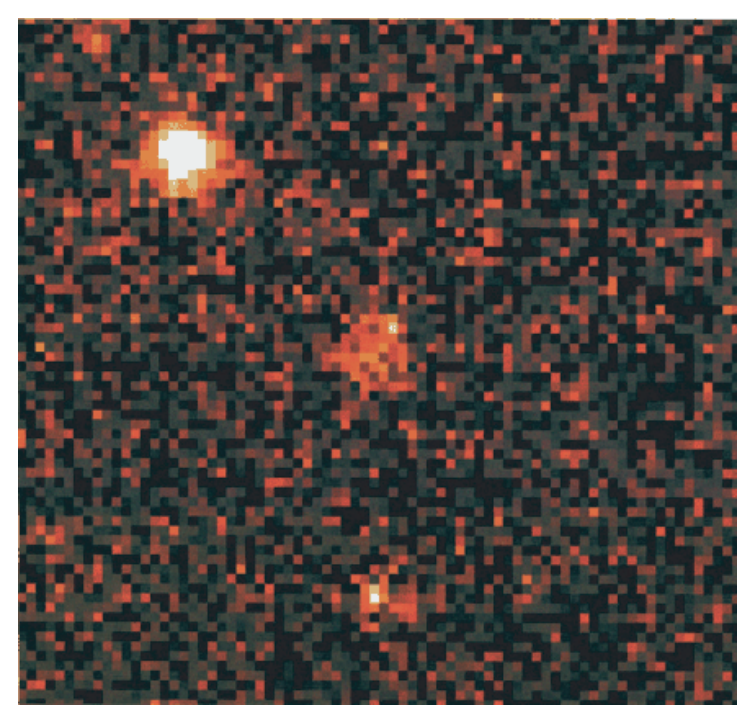
Greatest Mystery in Astrophysics



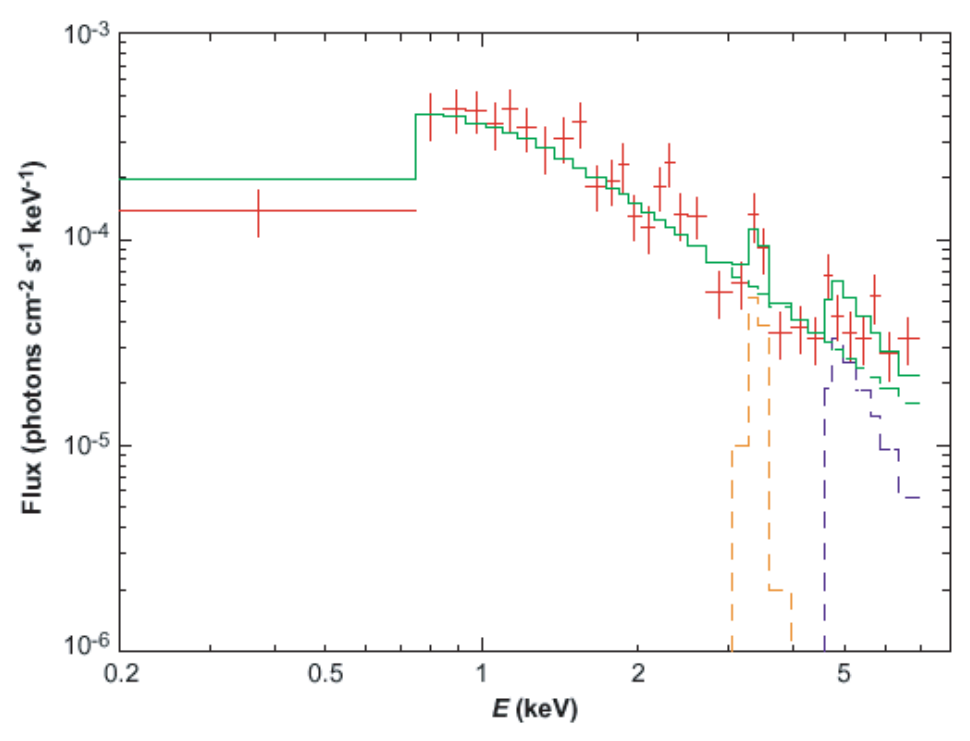
The mystery begins with the Unites States launching a satellite network in 1962 designed to detect high-energy nuclear detonations by the Soviets. Remarkably, very energetic bursts of gamma ray energy were detected not from Earth, but from outer space. Since their initial detection in 1962, these strange bursts have been steadily detected (totaling over 3000 detections) and have baffled and stimulated astronomers and physicists ever since.

In a Galaxy Far Far Away...



A major breakthrough in gamma ray burst (GRB) understanding was made by BeppoSax, when it observed an x-ray afterglow. This allowed scientists to pinpoint the location of the burst. Using the KECK Telescope, scientists were able to observe very high redshift in the host galaxy, and thus determine the GRB to be at the far reaches of the universe. The distance and luminosities imply enormous energy, on the order of 10^{53} ergs, making GRBs the most energetic events known in the universe.

Ferro Fireball



In the last few years iron emission lines have been seen in several GRB afterglows. These lines imply the presence of large amounts of iron, which strongly supports the association of GRBs with a supernova explosion. Analysis of the x-ray spectrum shown here by Piro et al. (2000) suggests the following conditions for the iron:

- One solar mass of iron
- e- density of 10^{10} cm^{-3}
- Distance of 10^{15} cm from the GRB

Supranova Model

Of all the models evaluated, the Supranova Model seems the most promising as a progenitor of GRBs, in that it best explains the occurrence of heavy elements in the spectra of afterglows detected from GRBs. The Supranova Model involves 3 distinct stages:

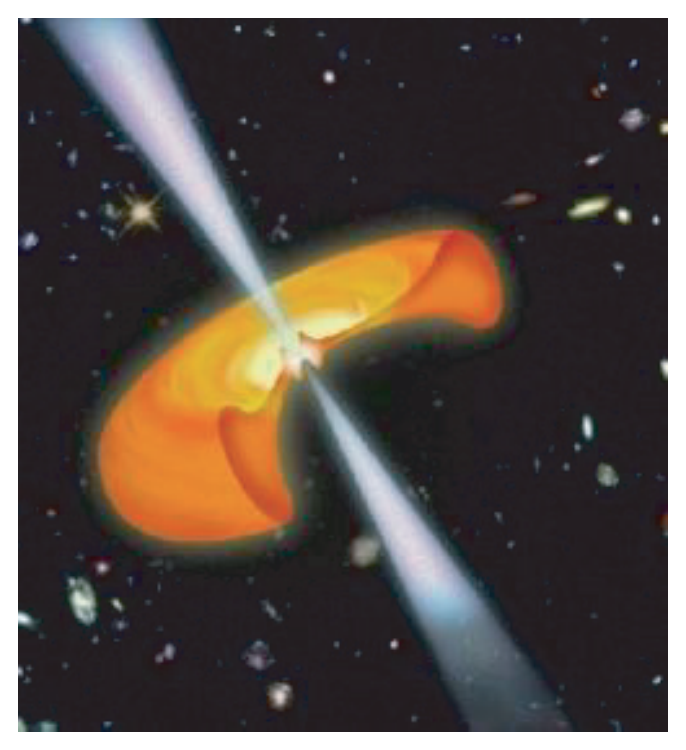
Stage I: A Normal Supernova

A massive, rotating star dies a violent death, ejecting its remnants into space at over 10,000 km/s. This supernova can be as bright as an entire galaxy. A supernova is visible as a bright source at the bottom of this image of a nearby galaxy (SN 1994D).

Stage II: Pulsar Wind Nebula

A rapidly rotating neutron star left behind by the supernova releases energy creating a bubble, or pulsar wind nebula (PWN), which clears out the ejected material around the star. The Crab Nebula, seen here, is the nearest PWN to Earth.

Stage III: The Gamma-Ray Burst

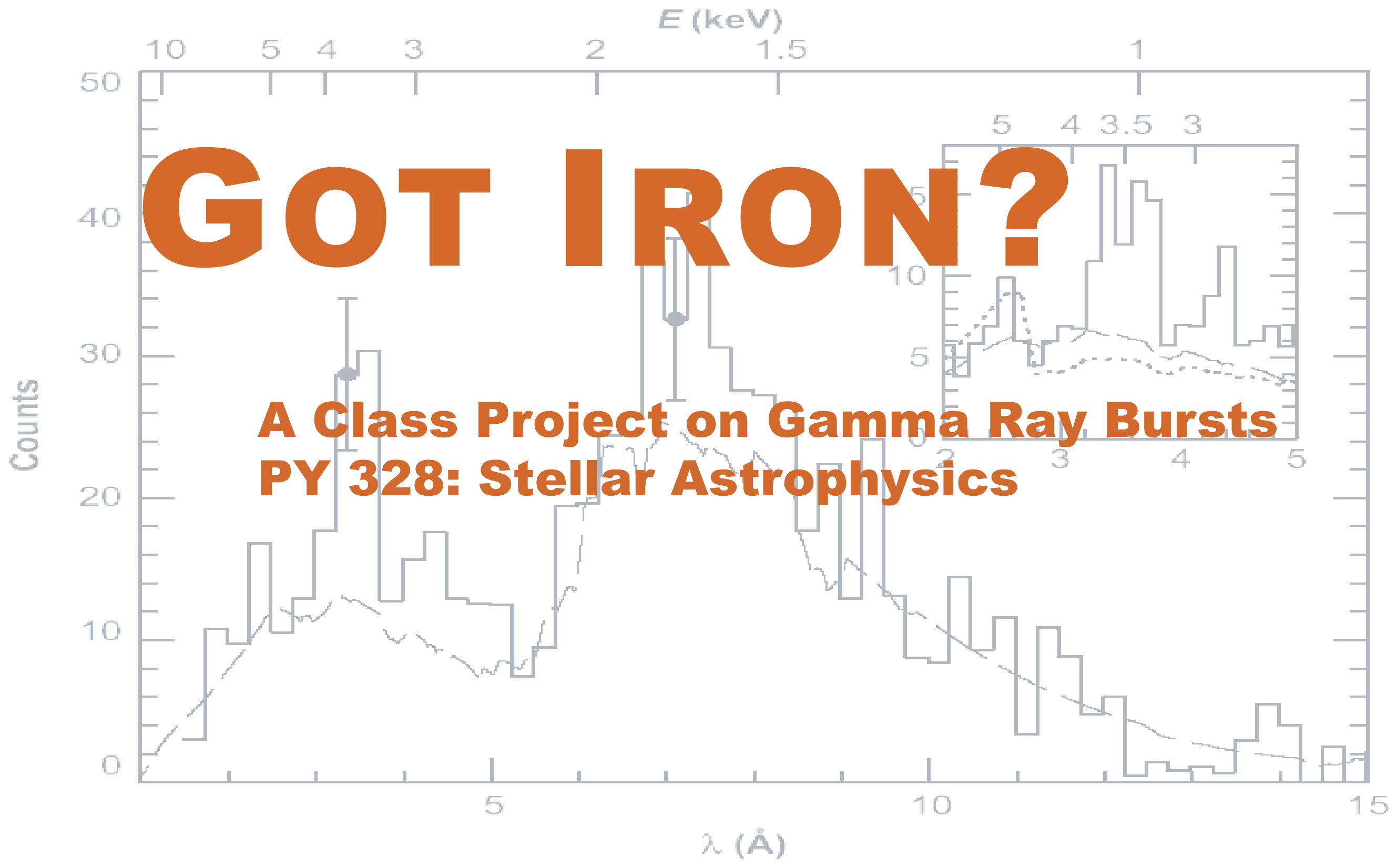


When the neutron star rotation slows down weeks or months later, gravity overcomes centrifugal force and the star collapses into a black hole. In the seconds following the collapse the rotational energy of the black hole is tapped to produce the GRB.

Can the model explain Iron Lines?

An natural consequence of the supranova model is the presence of large amounts of heavy elements, including iron, synthesized in the explosion. The PWN will sweep this material into a thin shell of dense gas. When the neutron star collapses to produce a GRB, the energetic photons from the burst light up the shell of iron.

Our Goal is to see if this postulated shell of iron around the pulsar bubble can explain the observed iron line emission.



Got Iron?

A Class Project on Gamma Ray Bursts
PY 328: Stellar Astrophysics

Eric Brunner
Warren Buff
Aaron Carpenter
Tera Crowe
Tony DeCaro
Paul Ehrenkaufer
Nick Featherstone
Noah Genzel
John Hardin
Ashley Harris
Rich Helle
Jeff Junker
Mark Lavin
Kevin Lee
Iyam Lynch
Tonya Mason
Megan Miller
Rob Pascale
James Perkins
Will Peterson
Ana Pinto
James Price
Sally Royo
Gerald Sears
Karen Spieler
Sam Thompson
Ralph White

A Spherical Pulsar Bubble: Analytic Theory

We can find the mass and density of iron swept up into a shell by computing the radius of the pulsar bubble using conservation of mass, radial momentum, and energy:

$$R_b = 6.4 \times 10^{15}\,\mathrm{cm}\left(\frac{L_{pr}}{10^{42}}\right)^{1/5}\left(\frac{E_{sn}}{10^{51}}\right)^{3/10}\left(\frac{M_{ej}}{M_\odot}\right)^{-1/2}\left(\frac{t}{100}\right)^{6/5}$$

where E_{sn} is the kinetic energy imparted to the iron ejecta by the supernova explosion, M_{ej} is the mass of iron ejecta, L_{pr} is the luminosity of the pulsar, and t is the time (in days) since the supernova explosion.

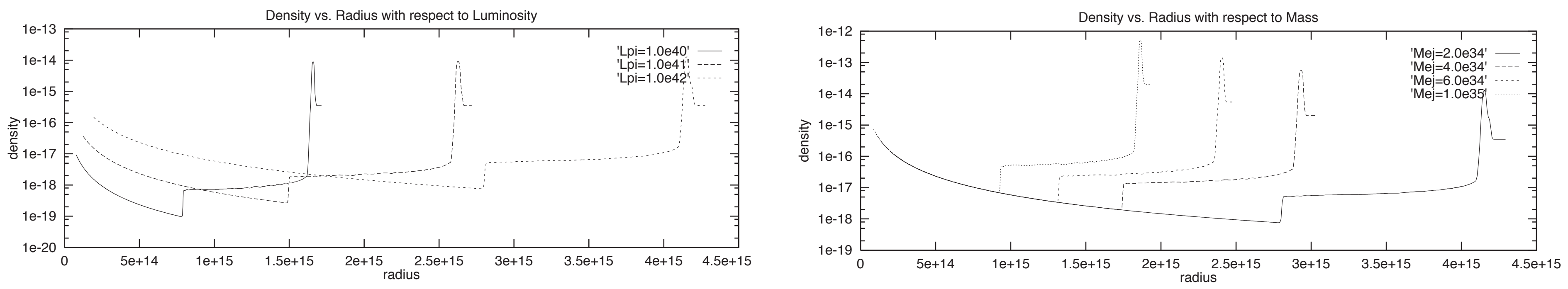
The total mass of iron swept up in the shell is

$$M_{Fe} = 0.2 M_\odot \left(\frac{L_{pr}}{10^{42}}\right)^{3/5}\left(\frac{E_{sn}}{10^{51}}\right)^{-3/5}\left(\frac{M_{ej}}{M_\odot}\right)\left(\frac{t}{100}\right)^{3/5}$$

The number density of electrons in this shell is

$$n_e \approx 10^9\,\mathrm{cm}^{-3}\left(\frac{E_{sn}}{10^{51}}\right)^{-3/2}\left(\frac{M_{ej}}{M_\odot}\right)^{5/2}\left(\frac{t}{100}\right)^{-3}$$

For our fiducial parameters we find good agreement with the parameters inferred from x-ray observations (Piro et al. 2000).



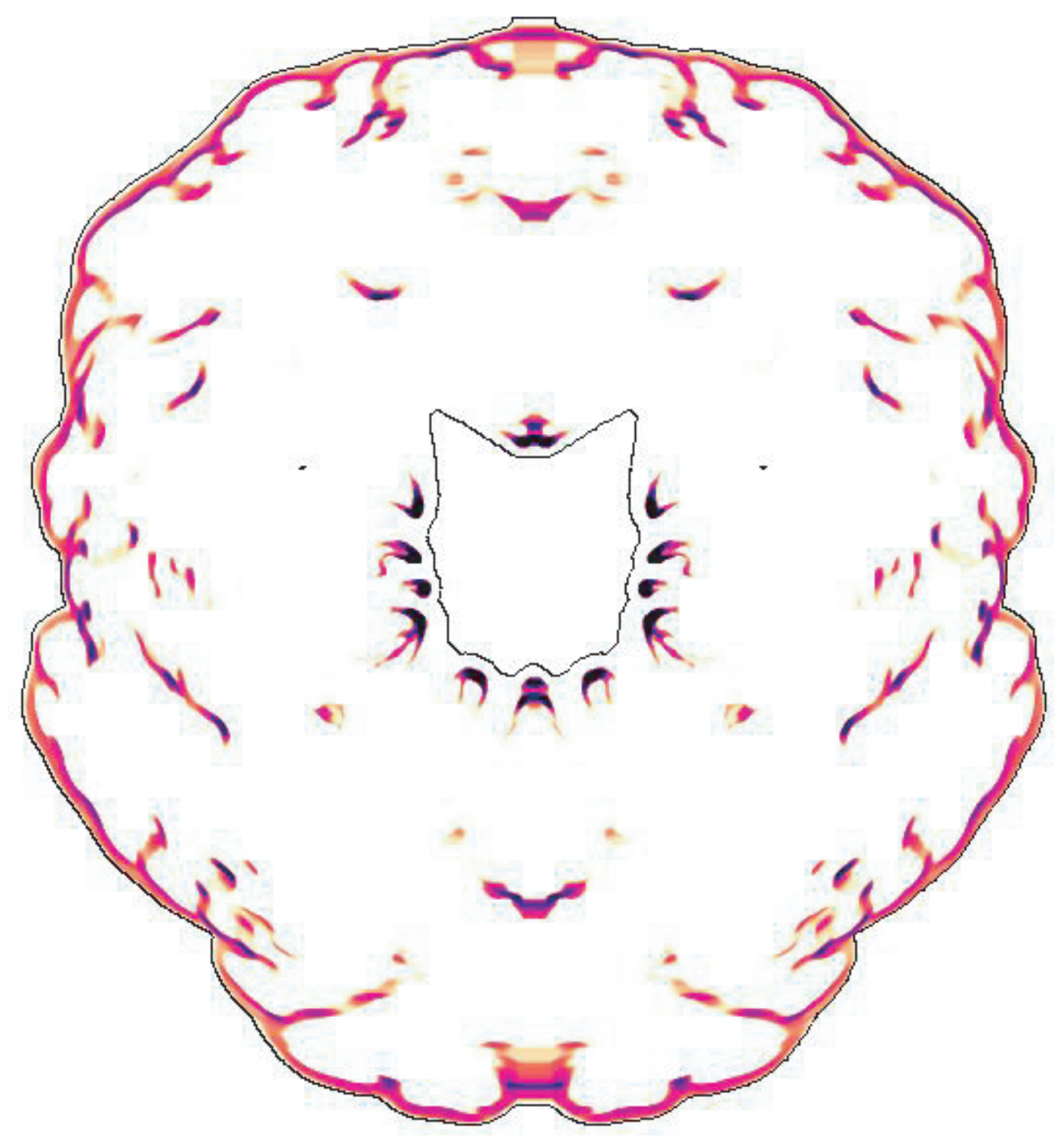
We can compute the radial structure of the pulsar bubble by evolving 1D hydrodynamic simulations. The results are shown above for different values of the supernova ejecta mass and pulsar luminosity. The shell of swept-up iron is the narrow peak of high-density gas near the maximum radius of each solution.

While this simple, spherical model explains the proper amount of iron at the right distance from the GRB, there is a problem with this model:

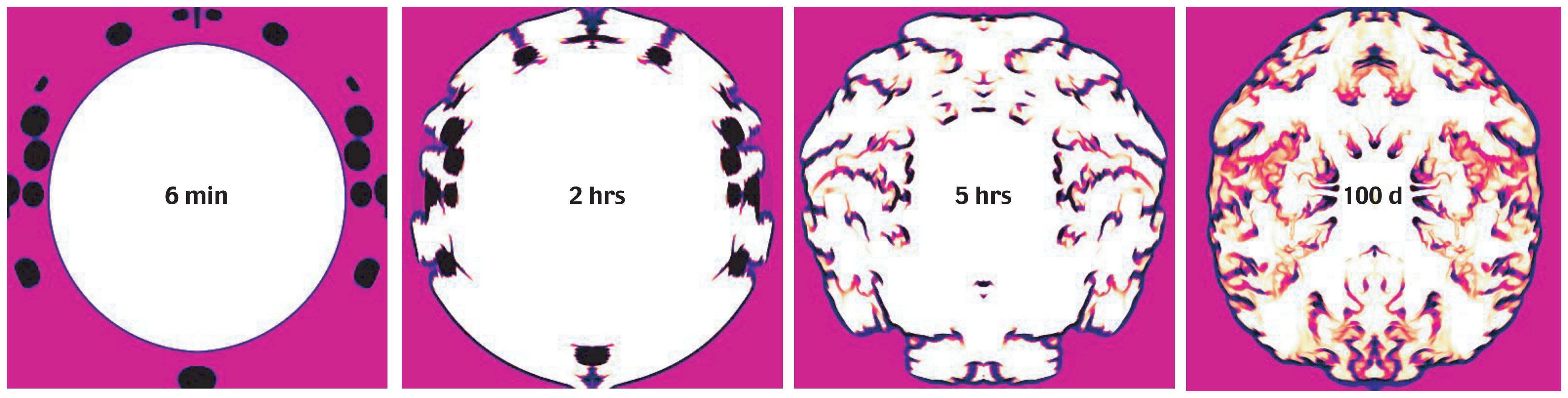
> *When the source of the GRB (a relativistic jet) reaches the shell, the collisions should produce a rapid rise in the afterglow emission. Yet the luminosity of the afterglow continues to decay for many days.*

To account for the steady decline in the afterglow emission we investigated two models that attempt to allow room for the GRB jets to propogate undisturbed to larger distances.

A Pulsar Bubble in Clumpy Supernova Ejecta



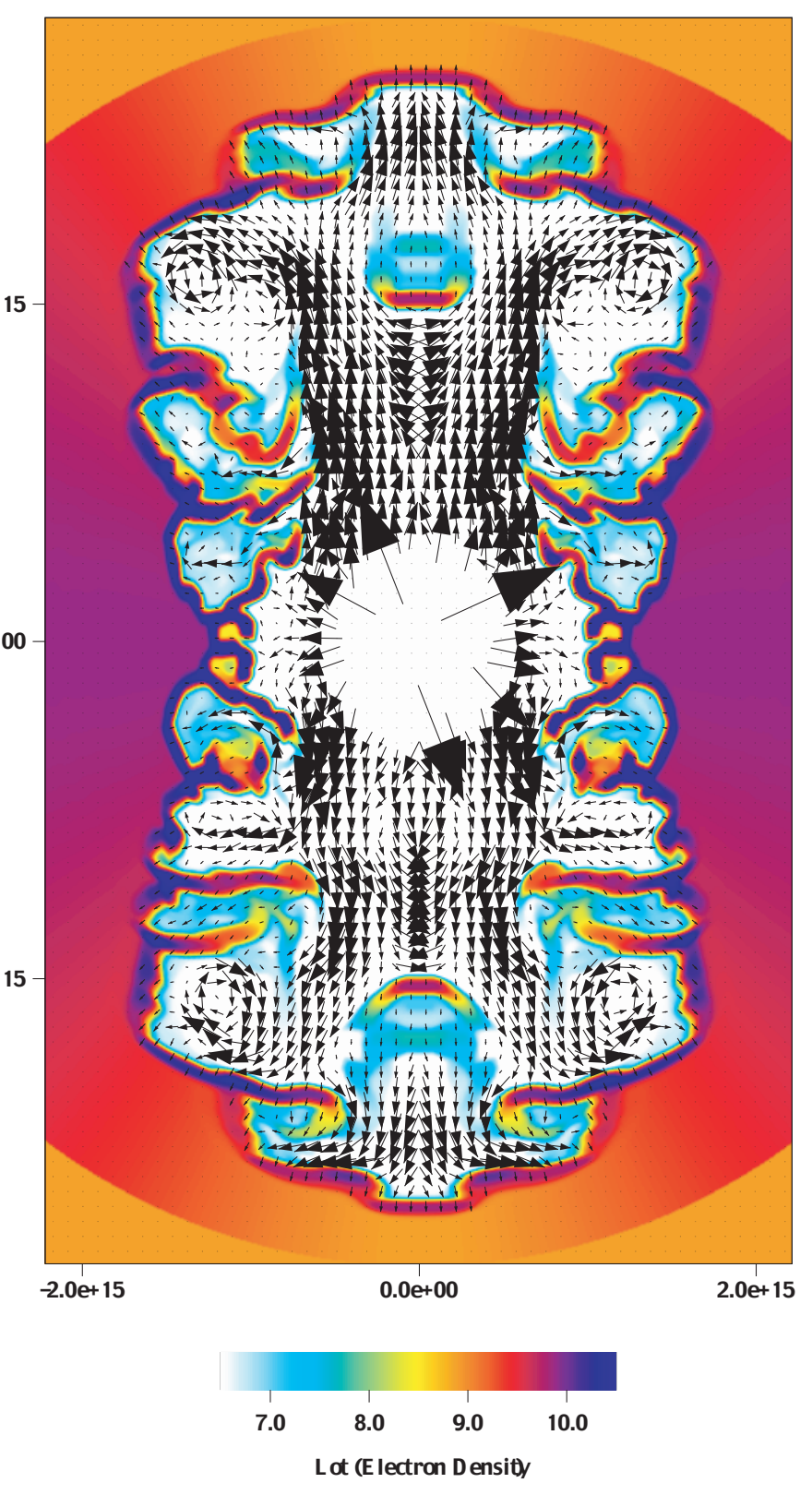
Color scale depicts gas density at 200 days after SN

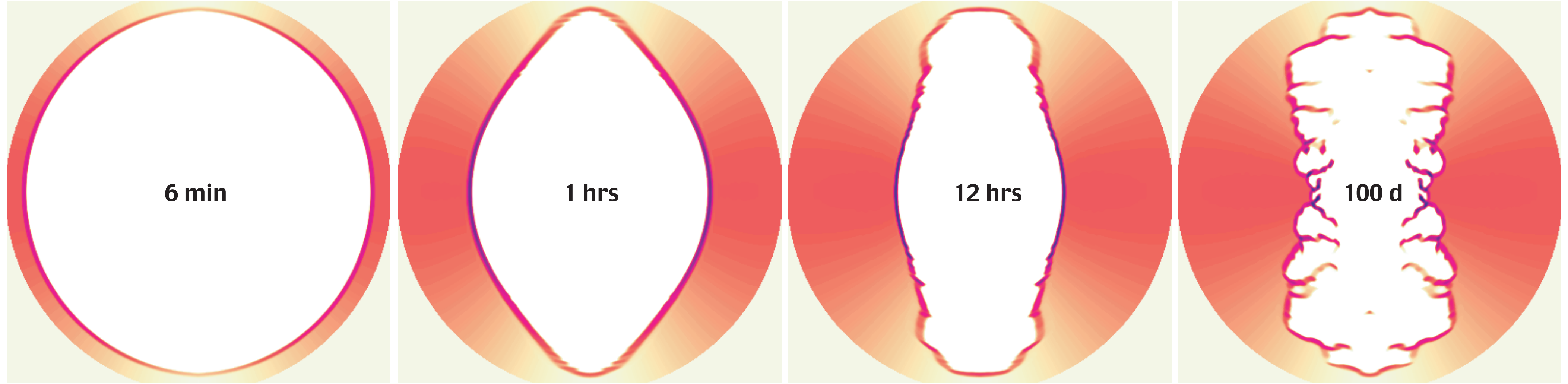


This model builds on the growing evidance that supernova ejecta is very clumpy. Here we modeled the ejecta as a uniform density gas embedded with very dense (200 times the ambient density) clumps of iron in the inner regions of the ejecta. The PWN runs over these clumps in the first few hours after the supernova explosion, leaving these clumps at a relatively small radius from the sit of the GRB. There is sufficient area for the GRB jets to escape this region without hitting any iron clumps.

After the PWN has swept around the clumps, the shell remains unstable. As a result, the interior of the bubble is filled with filaments of dense ejecta and the outer shell is no longer spherical.

A Pulsar Bubble in Asymmetric Supernova Ejecta





This model assumes that the supernova ejecta has an asymmetric density distribution, likely due to the rotation of the progenitor star. We used a factor of 10 greater density in the equatorial plane than along the axis of rotation. A PWN sweeps up the jecta, but because of the asymmetry the shell quickly (less than 1 day) becomes elongated along the poles. The shell of iron is 2.5 times farther from the GRB along the poles than the equator, allowing more time before the GRB jets reach the ejecta shell.

A consequence of the gas motion inside the PWN is that the shell becomes instable and we arrive at a morphology shown above. This instability can lead to smaller, denser clumps of iron than one might expect for a smooth, spherical shell.