Baade and Zwicky: "Super-novae," neutron stars, and cosmic rays

Adam S. Burrows[1]
Department of Astrophysical Sciences, Princeton University, Princeton, NJ 08544

In 1934, two astronomers in two of the most prescient papers in the astronomical literature coined the term "supernova," hypothesized the existence of neutron stars, and knit them together with the origin of cosmic-rays to inaugurate one of the most surprising syntheses in the annals of science.

From the vantage point of 80 y, the centrality of supernova explosions in astronomical thought would seem obvious. Supernovae are the source of many of the elements of nature, and their blasts roil the interstellar medium in ways that inaugurate and affect star formation and structurally alter the visible component of galaxies at birth. They are the origin of most cosmic-rays, and these energetic rays have pronounced effects in the galaxy, even providing an appreciable fraction of the human radiation doses at the surface of the Earth and in jet flight. Prodigiously bright supernovae can be seen across the Universe and have been used to great effect to take its measure, and a majority of them give birth to impressively dense neutron stars and black holes. Indeed, the radio and X-ray pulsars of popular discourse, novels, and movies are rapidly spinning neutron stars injected into the galaxy upon the eruption of a supernova (Fig. 1).

However, it was only with the two startlingly prescient PNAS papers by Baade and Zwicky (1, 2) in 1934 that the special character of "super-novae" (a term used for the first time in these papers) was highlighted, their connection with cosmic rays postulated, and the possibility of compact neutron stars hypothesized. (In the winter of 1933, Baade and Zwicky presented a preliminary version of these ideas at the American Physical Society Meeting at Stanford University.) To be sure, as early as 1921, in the famous Shapley–Curtis debate on the scale of the universe, Heber Curtis had stated that a division of novae into two magnitude classes "is not impossible" (3). However, before the Baade and Zwicky papers, astronomers had not developed the idea that supernovae, such as S Andromedae and the bright event studied by Tycho Brahe in 1572, must be distinguished from the more common novae. Moreover, before these papers, the concept of a dense "neutron star" the size of a city but with the mass of a star like the Sun, did not exist. In their own words (italics in original) (2): "With all reserve we advance the view that a super-nova represents the transition of an ordinary star into a *neutron star*, consisting mainly of neutrons. Such a star may possess a very small radius and an extremely high density." In addition, the energetic class of explosions identified in the first paper (1) as "super-novae" naturally suggested to the authors in their second paper (2) that they could be the seat of production of the energetic particles discovered by Hess in 1911 (4). Baade and Zwicky state (2): "We therefore feel justified in advancing tentatively the hypothesis that *cosmic rays are produced in the super-nova process*" (italics in original). Eighty years later, this remains the view of astrophysicists.

Fig. 1. A picture of the inner regions of the famous Crab Nebula captures emergent jets and the "Napoleon Hat" structure of surrounding plasma. The radio/optical/X-ray pulsar, a neutron star rotating at ~30 Hz, is buried in the center. The Crab was produced in a supernova explosion in A.D. 1054. Image courtesy of ESA/NASA.

Author contributions: A.S.B. wrote the paper.

The author declares no conflict of interest.

This article is part of the special series of PNAS 100th Anniversary articles to commemorate exceptional research published in PNAS over the last century. See the companion articles, "On super-novae" on page 254 in issue 5 of volume 20, and "Cosmic rays from super-novae" on page 259 in issue 5 of volume 20, and see Core Concepts on page ■■■.

[1] Email: burrows@astro.princeton.edu.

www.pnas.org/cgi/doi/10.1073/pnas.1422666112

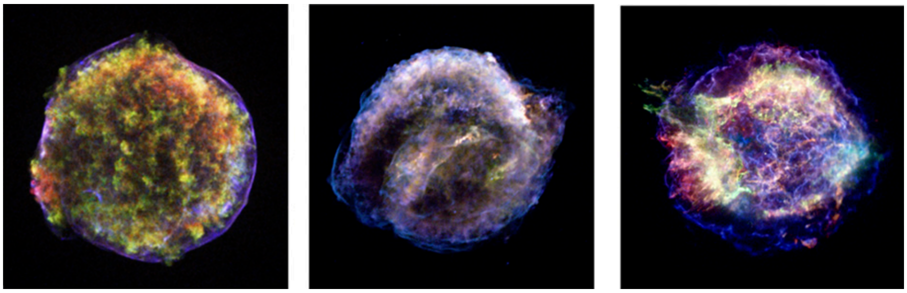

Fig. 2. False-color X-ray images of the Tycho, Kepler, and Cassiopeia galactic supernova remnants. The different colors approximately reflect different elemental compositions. Red traces iron, green traces silicon, and blue traces calcium and iron blends. These supernova explosions occurred in 1572, 1604, and ~1680 A.D., respectively. (*Left*, credit: X-ray: NASA/CXC/SAO, Infrared: NASA/JPL-Caltech; Optical: MPIA, Calar Alto, Krause et al.), (*Center*, credit: NASA/CXC/UCSC/Lopez et al.), (*Right*, credit: NASA/CXC/SAO/Patnaude et al.) Images courtesy of the Chandra X-ray Center; data originally published in refs. 16–18, respectively.

The concept of a supernova was rapidly accepted, and in the following years many examples were found (5–8). After all, the outsized blast waves that are the "supernova remnants" in our galaxy (Fig. 2), and the explosive transients seen in other galaxies ("island universes") that astronomers had recently demonstrated were outside our galaxy and distant, had therefore to be extraordinarily energetic. However, the concept of a neutron star was initially met with skepticism, despite the theoretical calculations of Oppenheimer and Volkoff (9), and it was not until the discovery of radio pulsars in 1967 (10) more than 30 y later—and their interpretation as spinning neutron stars the next year (11)—that the concept of a neutron star was accepted and mainstreamed. Today, we know of many thousands of radio pulsars and neutron star systems, and their study engages many in the astronomical community.

As might have been anticipated, most of the quantitative results presented in the Baade and Zwicky papers from 1934 (1, 2) have not survived. However, the authors were motivated to posit a neutron star by the extraordinary energy they concluded was required to explain their supernovae, and to produce energetic cosmic rays simultaneously, impulsively, and copiously. A neutron star would be very dense and, in the words of Baade and Zwicky, the "gravitational packing energy" would be very high (2). The authors had eliminated nuclear energy as too small to power a supernova, and believed they needed a nontrivial fraction of the rest-mass energy of the star. (Note also that the year 1934 was before we fully understood the nuclear processes that power stars.) This fraction Baade and Zwicky could obtain from the gravitational binding energy of a compact object with nuclear or greater densities. The neutron had just been discovered in 1932 (12) and was known to be neutral, and Baade and Zwicky imagined that oppositely charged protons and electrons could be crushed together to produce their beast. The modern view (13) is not extravagantly different, although one now quotes Baade and Zwicky for profound insight, not technical accuracy. Importantly, one type of supernova, the Type Ia, is indeed powered by nuclear energy. In fact, and ironically, all of the supernovae observed by Baade and Zwicky in the 1930s were of this type, not of the majority type currently thought to be powered ultimately by gravitation.

Many believe that Lev Landau predicted the existence and characteristics of neutron stars soon after the discovery of the neutron (14). However, as Yakovlev et al. (15) have clearly shown, Laudau was thinking about a macroscopic nucleus and nowhere in that paper was the neutron mentioned. Landau's paper (14) was in fact written before the discovery of the neutron, and incorporated the misunderstanding that quantum mechanics for nuclear processes required the violation of energy conservation. Hence, the appearance of Landau's paper in 1932 was a coincidence. However, Landau did address what is now known as the "Chandrasekhar mass" for white dwarfs, and his concept of a compact star was a creative departure.

More than 250,000 papers have been written since, with either the words "supernova" or "neutron star" in their title or abstract (according to NASA's Astrophysics Data System, adsabs.harvard.edu/abstract_service.html). Four Nobel Prizes in Physics have been awarded for work involving the supernovae and neutron stars in some way. As of 2014, more than 6,500 supernovae have been discovered. The theory of cosmic-ray acceleration in supernova remnants is now a well-developed topic in modern astrophysics. However, the leap of imagination shown by Baade and Zwicky in 1934 in postulating the existence of two new classes of astronomical objects, and in connecting three now central astronomical fields into one whole, still leaves one breathless. Even decades later, such a reaction continues to be a fitting tribute to these landmark PNAS papers (1, 2).

---

1 Baade W, Zwicky F (1934) On super-novae. *Proc Natl Acad Sci USA* 20(5):254–259.
2 Baade W, Zwicky F (1934) Cosmic rays from super-novae. *Proc Natl Acad Sci USA* 20(5):259–263.
3 Shapley H, Curtis HD (1921) The scale of the universe. *Bulletin of the National Research Council*, 2(part 3, No. 11):171–217.
4 Hess VF (1912) Über Beobachtungen der durchdringenden Strahlung bei sieben Freiballonfahrten. *Phys Z* 13:1084–1091.
5 Baade W (1938) The absolute photographic magnitude of supernovae. *Astrophys J* 88:285–304.
6 Baade W (1943) Nova Ophiuchi of 1604 as a supernova. *Astrophys J* 97:119–127.
7 Baade W (1945) B Cassiopeiae as a supernova of type I. *Astrophys J* 102:309–318.
8 Zwicky F (1940) Types of novae. *Rev Mod Phys* 12(1):66–86.
9 Oppenheimer JR, Volkoff GM (1939) On massive neutron cores. *Phys Rev* 55(4):374–381.
10 Hewish A, Bell SJ, Pilkington JDH, Scott PF, Collins R (1968) Observation of a rapidly pulsating radio source. *Nature* 217(5130):709–713.
11 Gold T (1968) Rotating neutron stars as the origin of the pulsating radio sources. *Nature* 218(5143):731–732.
12 Chadwick J (1932) Possible existence of a neutron. *Nature* 129:312.
13 Burrows A (2013) Perspectives on core-collapse supernova theory. *Rev Mod Phys* 85(1):245–261.
14 Landau LD (1932) On the theory of stars. *Phys Z Sowjetunion* 1:285–288.
15 Yakovlev DG, Haensel P, Baym G, Pethick C (2013) Lev Landau and the concept of neutron stars. *Physics Uspekhi* 56:289–295.
16 Krause O, et al. (2008) Tycho Brahe's 1572 supernova as a standard type Ia as revealed by its light-echo spectrum. *Nature* 456(7222):617–619.
17 Lopez LA, et al. (2009) Typing supernova remnants using X-ray line emission morphologies. *Astrophys J* 706:L106–L109.
18 Patnaude DJ, Fesen RA (2009) Proper motions and brightness variations of nonthermal X-ray filaments in the Cassiopeia A supernova remnant. *Astrophys J* 697(1):535–543.