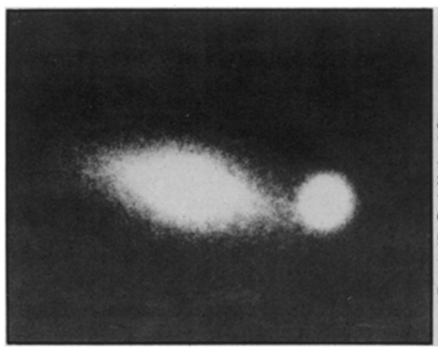
Supernovas

When a star goes off on its final explosive fling, it leaves behind much data and many questions for astrophysicists

BY DIETRICK E. THOMSEN



Howard French, Kitt Peak National Observatory

A supernova in an uncatalogued galaxy appeared as bright as 10^{10} of its stars.

Long before pulsars were found, Zwicky suggested that they leave behind small dense cores. The L. A. Times cartooned the main difficulty of observing them.

A supernova is the spectacular explosion of a star. Astrophysicists generally tend to regard it as the last act in a star's life, death with a bang, not a whimper. The dramatic appearance of supernovas has guaranteed them astronomers' attention for at least a millenium, but as of now, more than 900 years after the first recorded supernova observation, the data about them still raise more questions than they answer.

The first question simply has to do with numbers. How frequent are supernovas? Does their frequency vary according to type of galaxy? Do they happen often enough to be regarded as the usual end of a star's development, or are there many stars that just gently fade away without this explosive last fling?

Supernovas are divided into two classes according to the spectrum of the light given off by the explosion. Does this mean that two distinct classes of stars give two different kinds of explosion, or are the two types rather the ends of a continuum that spreads over many classes of star? What do the spectral data have to tell about the physics of the explosion and the things it may throw into space? Are the nuclei of heavy elements that are observed in the cosmic rays synthesized in supernova explosions?

Last, and extremely important, is the problem of the aftermath. Supernovas leave behind: a) neutron stars, b) black holes, c) pulsars, d) nebulous clouds observable by light and/or radio, e) any or all of the above, f) few or none of the above. It seems arguable from the evidence, but no more than arguable, that e is the correct answer. The notion that supernovas may generate neutron stars or black holes gives them a role in cosmology and the kind of astrophysics in which the theory of general relativity plays an important role, and so a session was devoted to supernovas at the recent Eighth Texas Symposium on Relativistic Astrophysics.

The earliest recorded supernova observation we have was by Chinese astronomers in the year 1054. As G. Tammann of the University of Basel reviewed it, there are only six certified examples of supernovas in our galaxy that have been observed from earth. They include those of 1006 (in the constellation Lupus), 1054 (the Crab nebula), 1184 (which yielded the radio source 3C58), the one observed by Tycho in 1572 ("brighter than Venus"), the one Kepler recorded in 1601 and the radio source Cassiopeia A.

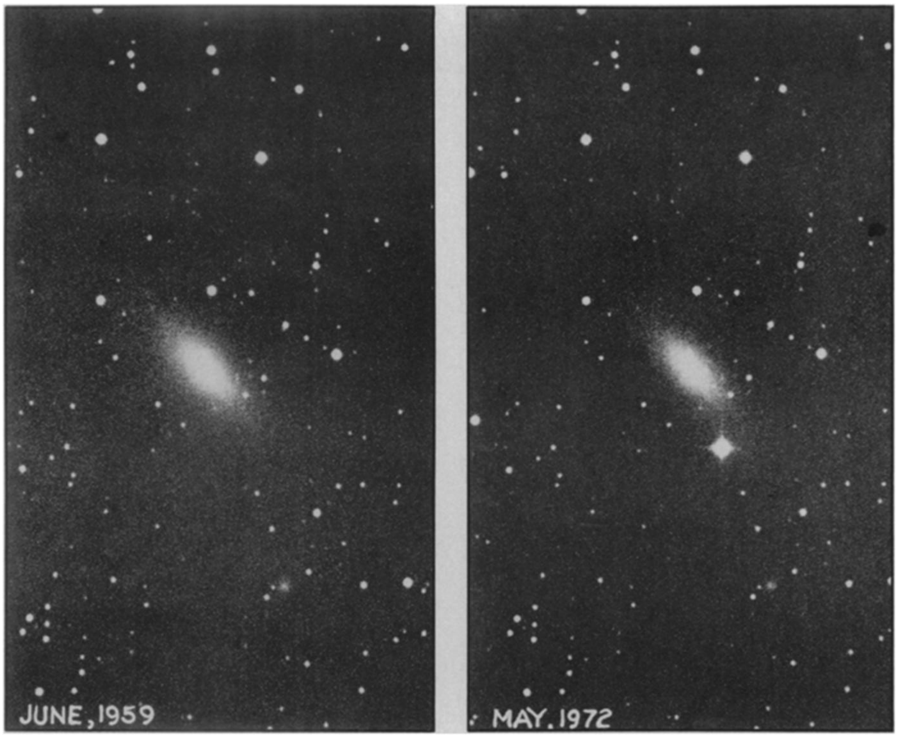
From this list one might at first suppose that supernovas were especially rare events, but a consideration of the locations of the reported galactic supernovas quickly shows that something is wrong with the list. As Tammann says, "There is a strong selection effect." Our ancestors saw only such supernovas as were near enough to be visible to the naked eye (all the cited sightings are before telescopes) and far enough from the plane of the galaxy not to be obscured by interstellar dust that lies very thickly in the plane. Applying various correction factors, Tammann arrives at an estimate of one supernova every 11 years, give or take about 2 years, in our galaxy.

With modern telescopes, supernovas can be seen in distant galaxies, and it is from these observations that what is known about supernovas is almost completely derived. In a region of space within 22 megaparsecs of the earth containing 400 galaxies, 77 bright supernovas (magnitude less than 13.5) have been observed since 1885. In the last 15 years (with more systematic observations), 33 bright supernovas have been seen within this sample. That gives an average of 2.2 per year throughout the sample, but since the observations are confined to the brightest, "The true figures can only be higher," Tammann says.

It turns out that the distribution of these supernovas by galactic type shows that most have appeared in the galaxies of spiral class Sc. (The other classes in the comparison include ellipticals; three other spiral types, SO, Sa and Sb; and irregularly shaped galaxies.) Tammann does not think this fact is of any physical importance, but a consideration of the distribution of Types I and Types II by location does lead him to some conclusions about the differences between the two types. Type I's occur in the flattened discs of galaxies and not in the spiral arms. They tend, he suggests, to represent the older population of stars and the less massive ones (less than and up to three times the sun's mass). "These stars die normally as white dwarfs," Tammann says. That is, they just fade away quietly as old soldiers are supposed to do without being vouchsafed a final burst of glory, but occasionally some trigger, possibly having to do with a binary companion, sets them off as supernovas. Type II's tend to be numerous in the spiral arms of galaxies and regions where clouds of atomic hydrogen are abundant. They seem to come from a young population of massive stars (more than five times the sun's mass).

What is known of the dynamics of supernova explosions comes from the study of their radiation. Visible light is the oldest and most widespread means of study, but recently, infrared, ultraviolet and X-rays have joined it, and the future may find a place for such exotic information bringers as neutrinos and gravity waves.

The most comprehensive observations of supernovas including the more recently



Charles T. Kowal, Hale Observatories

Before and after photos of the brightest appearing supernova since 1937. It happened in May 1972 in the galaxy NGC 5253. The official designation is supernova 1972e.

exploited parts of the electromagnetic spectrum are generally the most recent. Robert Kirshner of the University of Michigan reminds us what "recent" means in this context: The explosion "occurred a billion years ago; the light arrived here last Wednesday." So the latest observations actually deal with events that happened long before any of the recorded supernovas in our own galaxy. Unfortunately in Tycho's day or Kepler's, systematic spectroscopy was not possible, so we really will not know what a contemporary supernova looks like (could it be different?) until one blows off within a few light-years of the sun (we hope not too few).

According to Kirshner, most of the observations we have of the continuum background spectra of supernovas come from Type II, those that happen to evolved massive stars. The data, which Kirshner says agree rather well with theories worked out by Roger Chevalier of Kitt Peak National Observatory, indicate a hot, fast explosion that gradually slows and cools. Typical high temperatures run to 5,000° to 10,000° K for Type II supernovas; Type I's are even hotter, up to 20,000° K. A typical expansion velocity on the 40th day of observation is 4,600 kilometers per second. By the 125th day the velocity has slowed to 275 kilometers per second roughly. The explosion then trails off slowly with some differences in detail between the two types. The important point seems to be that the ejected material comes off in a thick shell rather than being spread all out. "You are rapidly seeing inward into the star," Kirshner says, and this is a point that is important to astronomers interested in the evolution and structure of stars because it is about the only way to see the inner layers of a star laid bare. Theoretically one should be able to see a pulsar if one is being made.

There is some question whether the data on record accurately represent the maximum temperature and expansion rates of supernovas. One of the pressing needs, Kirshner says, is for observations of the early stages of the explosion. Without them it is difficult to know exactly when the maximum happens, but early views are just the most difficult observations to get. Supernovas are usually not noticed until they are well on their explosive course, and even though astronomers have an international telegram system to notify them of transient phenomena such as supernovas, the astronomer who gets the notice still needs a telescope. Telescope time is rarely available instantly. Competition for telescope time is heavy and schedules are allotted far in advance. Astronomers who have waited months or years to set up a particular observation are usually not happy to give up some of their precious time and perhaps disconnect their equipment for the sake of a colleague who suddenly wants to look at a supernova. Kirshner hopes to avoid some of this problem in his future work. "I think we'll be able to get it [early observations] with the Michigan 52-inch telescope," he says.

In recent years astronomy has expanded from visible light into areas unimaginable to Tycho, Kepler or the eleventh-century Chinese astronomers: radio, ultraviolet, infrared, gamma rays. Ultraviolet observations are especially useful, says David Arnett of the University of Chicago, for determining early happenings in the supernova process, details of the explosive shock and the size and structure of the pre-supernova, the star as it is when it is on the point of blasting off.

A question that the application of gamma-ray astronomy may answer is whether the nuclei of heavy elements are made in the shock waves of supernova explosions. Theorists have proposed this, and it seems that only in such shocks and not in the less explosive chapters of a star's life are the conditions proper for such heavy-element synthesis. If the heavy elements are there, the characteristic gamma-ray wavelengths that they emit when energized should show up.

The future may see even more exotic inquiries, a search for neutrinos perhaps. If the compression of the star's core by the explosion turns most of its matter into neutrons—which would happen if it became either a neutron star or a black hole—lots of neutrinos should be produced. There is also one theoretical school that suggests that the supernova explosion is actually triggered by pressure built up by trapped neutrinos.

Finally there is the possibility of gravitational radiation, gravity's analogue to the light, radio and X-rays of electromagnetism. The explosion of a supernova and the implosion of its core are a large gravitational disturbance. They should produce a burst of gravitational radiation—if such radiation exists and can be recorded. Although there is an outstanding claim to the discovery of gravitational radiation that is almost a decade old, the present verdict of most physicists on the observability of such radiation would be "not proven."

In addition to waiting for the radiation from billion-year-old supernovas to arrive next Wednesday, astronomers can study the supernova remnants known in our galaxy. The most visible and famous of these is the Crab nebula, but the one most heavily studied lately is Cassiopeia A. As Chevalier describes the history of the investigation, Cas A was first found as a radio source. Later it was seen to have weak optical emissions and it has not been studied in X-rays, too. It appears to be the remnant of a supernova that exploded in 1657, give or take three years. Cas A, says Chevalier, gives a unique opportunity to see into a star that has blown apart. He says observation shows a number of things that supernova theory would like to find there as well as some oddities.

One such oddity is the manifest clumping of matter in the supernova remnant. This could mean that the explosion ejected matter in clumps. It could also mean that the original ejection was smooth, but that backward shock waves reflected into the outcoming matter caused it to clump later on. For the moment these data are ambiguous. On the other hand, the study of abundances of elements in the remnant

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yield values that are typical of those from hydrostatic nuclear burning late in the life of a massive star. This could mean that Cas A was a rather unusual supernova, a star whose nuclear burning had stopped before the supernova happened.

Finally there is question of supernovas and pulsars. Do supernovas leave pulsars behind? If so, in what proportion? If supernovas make pulsars, is that the only way to make pulsars? Theorists can make plausible scenarios for this or that answer, but the only observational data we have are statistical, and as Joseph Taylor of the University of Massachusetts puts it, this "direct evidence is weak." There are only two definite, completely accepted identifications of pulsars with supernova remnants, the Crab nebula and the Vela pulsars. There are many ways to explain the lack of coincidence, and Taylor's talk was devoted to examining their plausibility. It could be that most supernova remnants do not glow for very long, so that pulsars outlast them. It could be that the explosion gives the pulsar a velocity that usually shoots it out of the supernova remnant. Those are two reasons for pulsars without known supernova remnants. To explain supernova remnants without pulsars one can say that pulsars do not live very long, and there is in fact an example of a seemingly very short-lived pulsar that can be cited in support of this point, PSR 0904, which was discovered six years ago, but is no longer observable. Again one can say that pulsar emissions are too weak for us to see most of them at our distance from the supernova remnants. Another possible argument is based on the theorists' assumption that pulsar radiation is emitted in a narrow pencil beam from a spot on the rotating surface of the body. If that pencil beam doesn't cross our line of sight, we don't see the pulsar.

Many of these arguments seem plausible when examined in detail. The questions therefore remain open. What we need is to see a supernova explode and leave a pulsar behind or to see a pulsar appear by some other process, or both. And we may wait a long time for the chance of seeing either. □

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lated events separated in space and time, but a massive, complex eruption." As far as we presently know, continues Sheets, the eruption occurred in three stages, two ashflows (glowing avalanche) and an airfall ash. The ashflows, consisting of incandescent clouds of pumice, ash and gases, rolled downhill and buried villages and forests in their paths as far as 45 kilometers from their source. Shortly thereafter, perhaps hours to weeks, the airfall ash was deposited in a more uniform blanket over the countryside.

How would the ecology have been affected by such a calamity? Comparative geology provides some answers. Parícutin Volcano, 320 kilometers west of Mexico City, erupted in 1943 and continued active for nine years. The case of Parícutin, though a much smaller eruption than Ilopango, is fortunate for our comparison with the El Salvador eruption, says Sheets, owing to Ken Segerstrom's exhaustive study (USGS Bulletin 965A) and to the fortuitous situation of a high degree of climatic similarity between the Parícutin area and highland El Salvador.

The Mexican eruption wreaked havoc with critical human resources. Radical alterations in surface and groundwater flow were noted. Many springs either dramatically increased or decreased their flow; some new springs appeared and some old springs completely dried up. Large areas of land were deforested, along with all crops, shrubs, grasses and other plants. Plants are quite vulnerable to ashfalls, owing to smothering and structural overloading as well as to chemical attack. Animals die from inhalation and from ingestion of chemical-laden ash on plants they try to eat. Plant and animal life in both fresh and salt water is very sensitive to damage by tephra. In areas on land where plants were not killed by the actual ashfall, windblown ash, with its extremely sharp edges, has been known to "mow down" plants.

During the first year after the ashflow from Parícutin, no land covered by more than 10 centimeters of ash could be cultivated. Schemes were devised to counteract the effects of the ash, but few were successful during the next four years. It has been estimated that 200 years will be necessary to reestablish normal forest growth near Parícutin, and an even longer time period to recover from the severe erosional effects. "From this," concludes Sheets, "a 200-year devastation and abandonment of much of the Southeast Maya Highlands would not be unrealistic, in that the Ilopango ash was more damaging, more extensive and more voluminous." Virtually overnight, he says, the lush, tropical vegetation of much of El Salvador must have changed into a white desert devoid of almost all life.

Even in areas of southern Mesoamerica not directly damaged by ashfall, indirect effects may have been felt in a number of ways. Long-range floods and migrations of survivors may have been the most common repercussions, says Sheets. Extensive deposits of mud in north and central Belize and northwestern Honduras suggest that flooding did take place toward the end of the Preclassic era. Flooding in the lowlands could have been caused by ash damage to plant cover in the headwaters of the lowland rivers, resulting in increased runoff.

What happened to the people while all of this was taking place? Sheets estimates (conservatively, he says) that the environmental impact of the tephra-fall was greater than the Preclassic Mayan technological capacity to adjust and continue their agricultural adaptation over an area of 3,000 square kilometers. The density of settlement was high in the late Preclassic, because the Southeast Maya Highlands had been settled by agriculturists for more than a thousand years preceding the eruption, and archaeological evidence indicates a steady population growth throughout the Preclassic. Even so, says Sheets, if we use a minimal population density figure of 10 people per square kilometer, some 30,000 people would not have been able to continue living in the highlands. Did they actually migrate to the lowlands? Several lines of investigation suggest they did.

At Barton Ramie during the late Preclassic (between 100 B.C. and A.D. 300) a number of cultural and material events occurred at approximately the same time, and Sheets suggests that they may have been interconnected. These changes include a more than doubling of population as evidenced by a more than twofold increase in house occupations, as well as new ceramic characteristics. Among the ceramic changes several types appear (including the distinctive mammiform tetrapod vessels) that are so similar to sub-ash ceramics in El Salvador as to be indistinguishable by ceramicists working at Barton Ramie and Chalchuapa. These, as well as several other types of artifacts, all occur developmentally at Chalchuapa but suddenly at Barton Ramie.

With such evidence to go on, it appears that one intriguing question about the Maya has been answered. The fact that the lowlands received a major cultural input from the highlands in late Preclassic times does not imply that the sophisticated Classic civilization derived from the highland culture, but it does offer clues to the eventual development of one of the most highly evolved pre-Columbian civilizations. It is likely, for instance, that the sudden arrival of large numbers of people on the peripheries of the "core area" necessitated an intensification of social and political mechanisms, therefore accelerating the rate of cultural development.

"Right now," concludes Sheets, "we have the framework. We know that there was a massive natural disaster. Now we need to work out the details." Having been fascinated with the whole question for at least the past eight years, Sheets is eager to get back to El Salvador with a full team (including geologists and pollen and soil experts) in order to more completely study the ancient eruption and its effects. As these and other details are worked out, we may eventually come to know (and learn from) the ancient civilizations of the New World as we have from those of the Old World. □