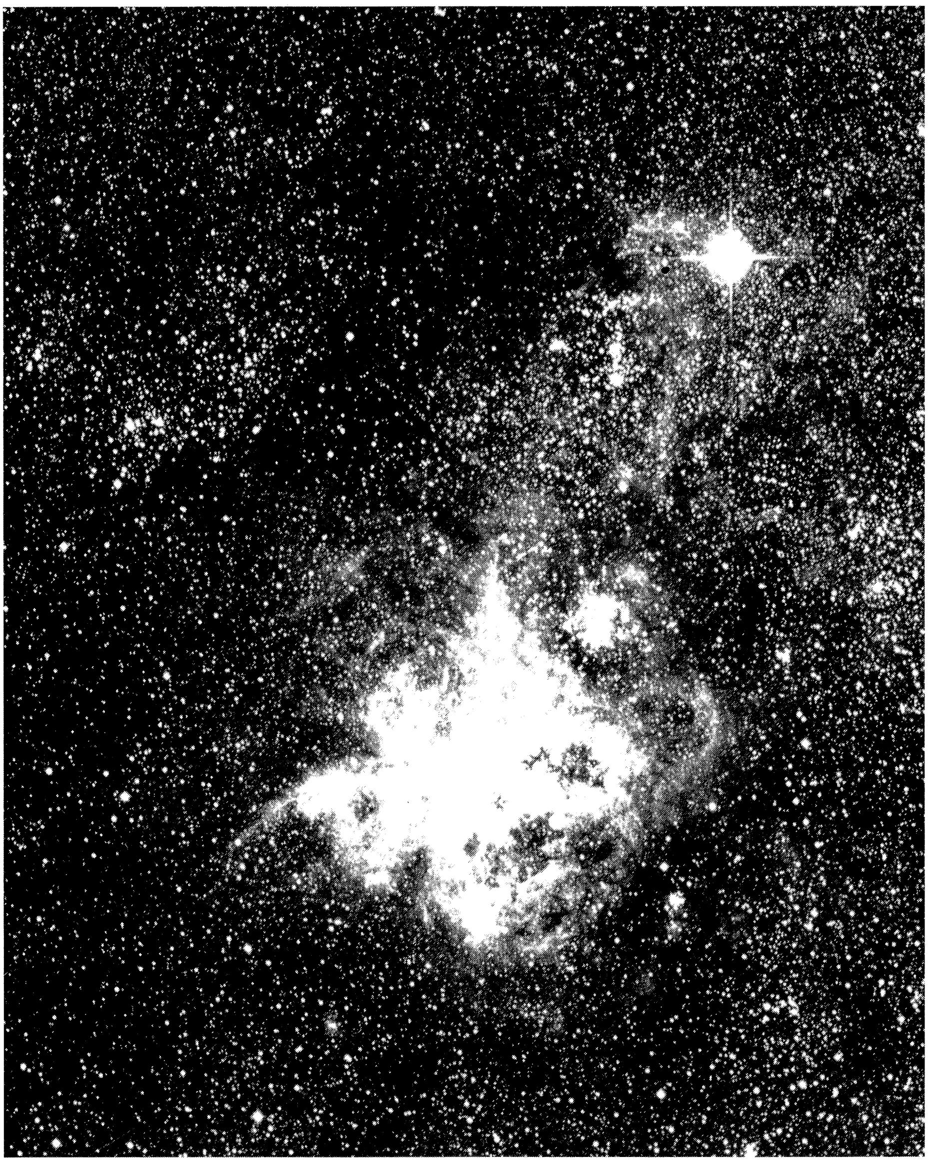
The great supernova of 1987

Despite their apparently very different objectives, astrophysics – the study of the largest structures in the Universe – and particle physics – the study of the smallest – have always had common ground. On 23 February 1987 a supernova explosion provided additional impetus to reinforce these links. In this article, David Schramm of the University of Chicago and the NASA/Fermilab Astrophysics Center, explains why.



SN 1987 A.

One of the most spectacular events in modern astrophysics occurred on 23 February 1987, when light and neutrinos from a supernova explosion in the Large Magellanic Cloud (LMC) first reached Earth. The LMC (a satellite of our Milky Way Galaxy) is 170,000 light years away, making the event, codenamed SN 1987A, the closest visual supernova since Kepler observed one almost 400 years ago.

Most of our knowledge of supernovae has come either from observations of outbursts in distant galaxies, too far away to obtain neutrinos, or from studies of old remnants in our Galaxy, thus missing the fireworks.

Having a supernova blast off relatively nearby while neutrino and electromagnetic radiation detectors were in action has been fantastic. In addition, the pre-supernova star was identified as a blue giant rather than a red giant supernova stereotype.

The detection of the initial neutrino burst made the supernova a weak interaction laboratory as well as founding extra-solar system neutrino astronomy. The supernova also proved that our ideas about element formation in exploding stars were basically correct. In particular, the gamma rays from radioactive cobalt-56 indicated that heavy elements had been 'cooked' – nucleosynthesis had indeed occurred.

This supernova also might affect estimates of stellar collapse rates in our Galaxy. In particular, if many blue stars collapse, then there could be many dim Type II supernovae that were missed in previous supernova rate estimates. Another exciting ingredient was the recent report of a 0.5 ms pulsar remnant in the supernova. This led to a lot of speculation but has now been withdrawn.

Supernovae – lore and laws

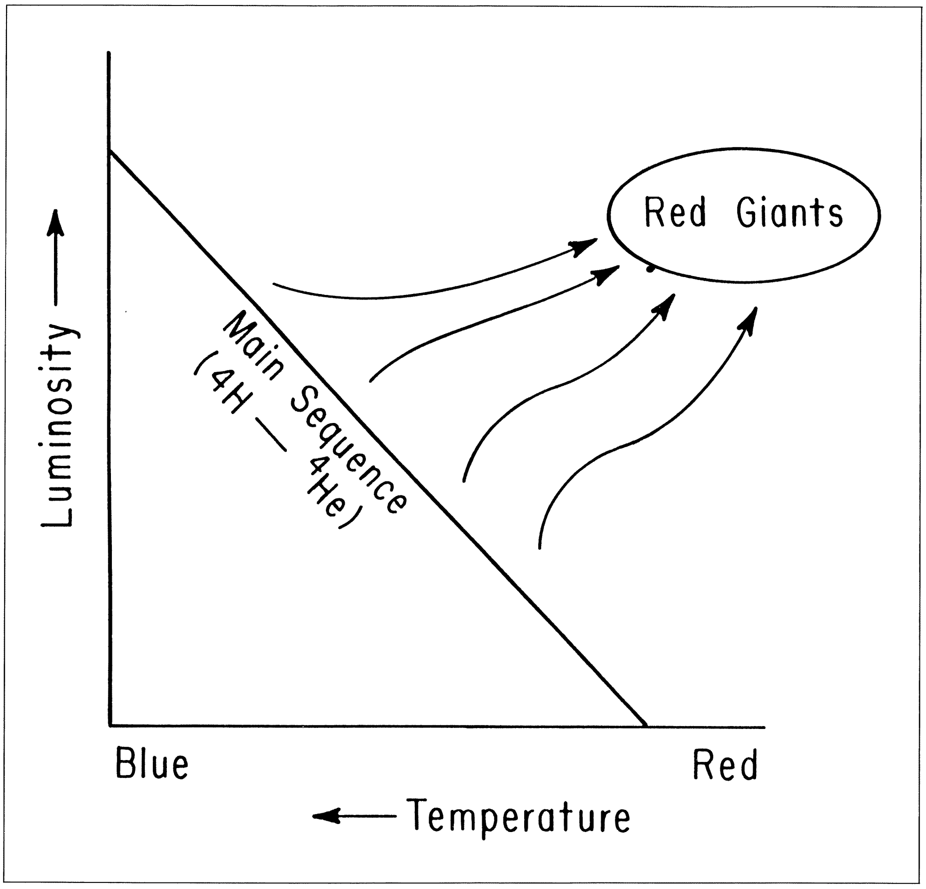
Astronomers classify supernovae by whether or not they have hydrogen: Type I have no hydrogen, Type II do. Supernova explosions also fall into two categories – nuclear detonation (when the pressure of gravitation pushes the interior temperature of a star to thermonuclear ignition) and gravitational core collapse (when gravitation crushes the atomic nuclei, producing a neutron star – see box). SN 1987A had hydrogen, so it is definitely Type II, and it had the neutrino footprint of core collapse.

The star which exploded was definitely the blue supergiant Sanduleak –69 202, estimated to be about 20 times heavier than the sun. Massive stars (more than about ten solar masses) have been generally assumed to be the progenitors of Type II supernova, and SN 1987A confirms this.

Such stars eventually evolve to an onionskin configuration with an iron core surrounded by successive shells of silicon, oxygen, neon, carbon, helium and an outer envelope of hydrogen. This structure develops through various stages of nuclear burning. The first stage is hydrogen burning to helium, when the outer surface temperature and luminosity are related by the main sequence line on Figure I. Our sun is currently on the main sequence. When the core helium mass reaches a critical level, it starts to collapse under its own gravity until it gets hot and dense enough for the helium to burn to carbon. As this core collapses, the outer envelope expands and the star becomes a 'red giant'.

The next stage occurs when the

Figure 1 – Stars are characterized by a luminosity/temperature chart (Hertzsprung-Russell diagram). Heavier stars are found from the upper left of the 'main sequence' (which includes the sun).



Supernova encounters of the second type

In a star more than about ten times heavier than the sun, the gravitational pressure can retain a thermonuclear furnace generating successive layers of heavier elements – hydrogen on the outside, then helium, then carbon, neon, oxygen and silicon, accreting a core of nickel, cobalt and iron, the most tightly bound nuclei, where the thermonuclear chain fizzles out.

In the 1930s Subramanyan Chandrasekhar pointed to a critical mass, about 1.4 times the mass of the sun, when stellar material succumbs to the compression of gravity.

At about the same time Fritz Zwicky had suggested that under extreme conditions, atoms could be crushed, with orbital electrons being pushed into nuclei, producing neutrons and neutrinos, and forming a neutron star of uniform nuclear density, a few cubic centimetres weighing hundreds of millions of tons!

Such compact nuclear matter is highly incompressible, and the gravitational collapse of the metallic core bounces back as a mighty shock wave, blowing apart the outer layers of the star. The energy released in such a supernova is enormous – as though everyone on Earth were to explode a million million million megaton hydrogen bomb at the same time – outclassed only by the Big Bang itself!

Such a supernova (Type II) produces two signals – an initial burst of neutrinos as its inner core collapses, and a subsequent wave of radiant energy as the shock wave bounces back. The 1987 supernova was the first time that physicists had been equipped to catch these neutrinos. It was also the first time that a supernova had lit up in a well-mapped part of the sky, so that astronomers were soon able to identify the culprit 'progenitor' star.

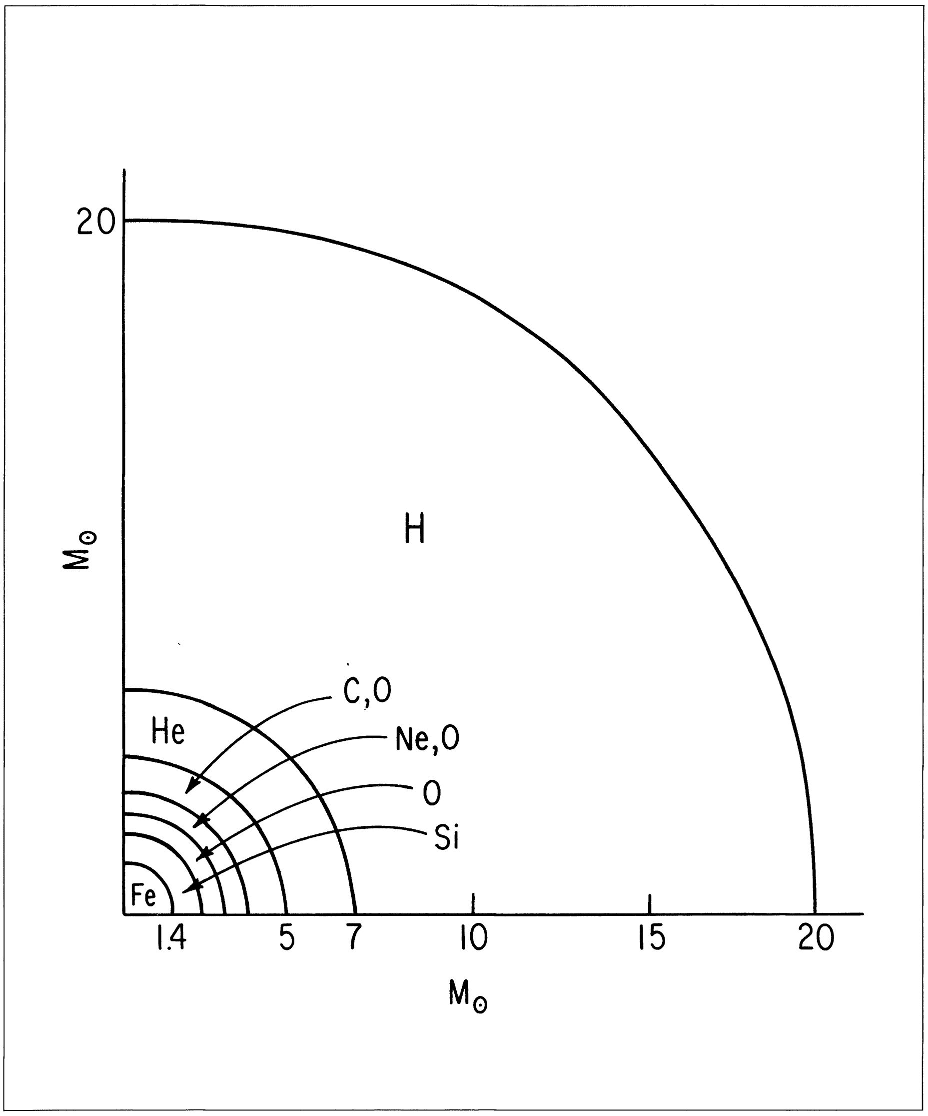


Figure 2 – A schematic cross-section of a star of about 20 solar masses, showing successive formation zones of heavier elements. Only the dominant elements are shown, significant amounts of nearby alpha-particle type nuclei also being present. When a supernova explodes and its iron core collapses to form a neutron star, several solar masses of heavy elements will be ejected. As Fred Hoyle first suggested in the 1940s, this could be the origin of the bulk of heavy elements.

carbon ashes of helium burning reach a critical mass and begin to collapse. Carbon cores go critical at the Chandrasekhar mass, about 1.4 solar masses. Because of matter evaporation (like the solar wind) stars lighter than about ten solar masses never get carbon cores this large, and so don't burn carbon, settling down instead to become white dwarves. On the other hand heavier stars do eventually go through carbon burning, followed by several successive stages before reaching iron (Figure 2). Here the burning sequence stops because iron has the maximum nucleon binding energy of any nucleus.

After the carbon burning stage, the centre of the star is so dense that energy produced by burning cannot radiate, and escapes mainly as neutrinos. Since these particles flow unscathed through the outer part of the star, these regions have no knowledge of what is happening inside. Thus once a star becomes a red giant, it is difficult to tell whether its core is burning helium or is iron on the verge of collapse. Furthermore the outer envelope may puff up and be blown off, or may contract due to hydrogen-helium mechanisms that have nothing to do with the interior goings-on.

The most discussed although not totally unexpected feature of the progenitor Sanduleak –69 202 is the fact that it was a blue supergiant. Standard descriptions for progenitors of Type II supernovae generally assume red supergiants. Such supernova lore was naturally biased, since standard Type IIs observed in distant galaxies require a large progenitor to achieve their high luminosities, and low luminosity, blue progenitor Type IIs would be easily missed. However even before 1987 it was known that massive blue stars could also undergo final collapse, depending on convection, mass loss, and composition. SN 1987A ultra-violet observations reveal the previously ejected red giant envelope as a circumstellar shell about 0.7 light years around a progenitor which was once red and subsequently eroded to blue.

Detailed nucleosynthesis calculations indicate that oxygen and nuclei from neon to calcium are produced in approximately solar proportions in massive stars and associated Type II supernovae, while carbon is somewhat underproduced. While there is general qualitative agreement on this, numerical results differ considerably. Nevertheless it was expected that the 1987 supernova should show significant levels of nuclei from oxygen to iron.

The amount of ejected iron from a Type II supernova is sensitive to the temperatures and densities near the boundary between the col-

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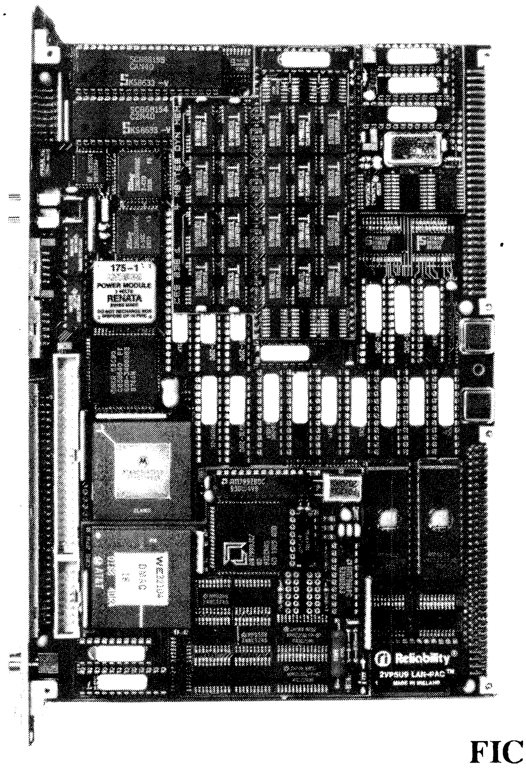

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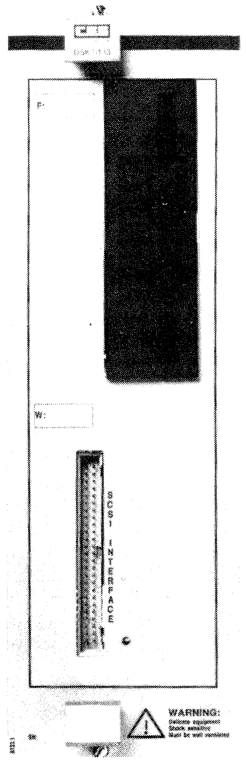

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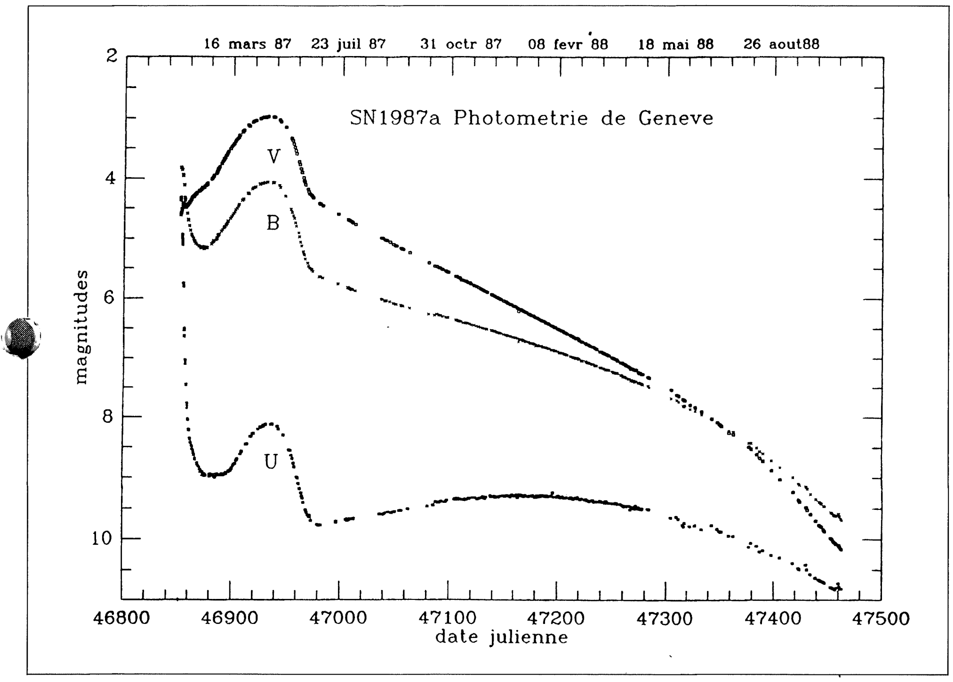
Figure 3 – Visual signal from the 1987 supernova as seen by the Geneva group using the European Southern Observatory.



lapsing core and the ejected material. The strength of the rebound shock shows both the extent to which silicon and intermediate mass nuclei are converted to iron and the rebound velocity due to the incompressibility of the core.

Iron production in SN 1987A determines the detected gamma ray signal and the role of decay heating in later stages. As iron is primarily formed from alpha particle nuclei with equal numbers of neutrons and protons, nuclei of mass 56 are formed as nickel-56, which decays with a 6.1-day half-life to cobalt-56, decaying in turn with a 79-day half-life to iron-56. The longer cobalt lifetime enables gamma-rays to be detected for a year or more after the initial explosion. By following the gradual fading of the supernova (Figure 3), astrophysicists estimated that it ejected 0.075 solar masses of cobalt-56. In addition, NASA's Solar Maximum Mission (SMM) space probe picked up the characteristic gamma rays less than nine months after the explosion, proving that fresh cobalt-56 had been synthesized in SN 1987A and confirming a prediction made twenty years earlier, as well as vindicating the arguments for gamma-ray line astronomy.

Following the light curve

Observations in Chile, Australia, New Zealand and South Africa gave a precise picture of how the light from SN 1987A varied with time (Figure 3). After its initial sighting, when the progenitor star's humble 12th magnitude shot up to about 6th magnitude, the supernova gradually intensified over the next 90 days, eventually reaching 3rd magnitude.

The 1987 Supernova differs from 'typical' supernovae observed in other galaxies, most, if not all, of these differences deriving from its origin as a blue star (radius 3 x 10^{12} m) as opposed to a red giant (radius 10^{13-14} m). Blue supergiant envelopes are smaller, denser and have steeper density gradients, giving higher velocities and converting more supernova energy into released kinetic energy, at the expense of radiative output. In addition, the time between collapse (neutrino emission) and the shock emerging from the surface (first light) would be hours for a blue star rather than days for a red giant. In 1987 this time lag was about three hours.

Hydrodynamic models indicate that the rapid rise in the initial visible light from SN 1987A ties in with a collapse at the same time as the emission of the detected neutrinos. It seems likely that the luminous energy over the first hundred days came from shock deposition and atomic recombination. The subsequent fading, with a half-life of 79 days, suggests that 0.075 solar masses of nickel-56 were ejected.

Remnant expectations – neutron star or black hole?

An important and still outstanding question is the character of the supernova's remnant. As well as giving neutron stars, the massive star progenitors of Type II supernovae can produce black holes. If the remnant core mass exceeds the limit for a stable neutron star (about two solar masses), the gravitation is so strong that a black hole is formed. Standard assumptions for the Sanduleak star favour a 1.4 ± 0.2 solar mass remnant, suggesting a neutron star, unless later accretion occurred.

Neutron star or black hole? The question should soon be answered. The supernova is no longer fading, having recently levelled off at value

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consistent with pulsar powering. A report of a 0.5 ms-period pulsar observed for 15 consecutive 30-minute intervals in January 1989 showed no variations in timing down to the 10^{-14} level, however this report has now been withdrawn.

Any pulsar should eventually show up as the debris thins out, and especially when the satellite ROSAT flies later this year and looks for the X-rays from the young neutron star. A fast rotating pulsar (such as that suggested by the initial report) would severely constrain the nature of nuclear and/or quark matter – only very soft matter theories can be consistent with such high rotation. In fact most nuclear matter theories had trouble with the 0.5 ms period pulsar.

Whatever the remnant turns out to be, the 1987 supernova has already taught us a lot. We now know that blue as well as red stars collapse, and that supernovae from the former are less bright. The cobalt-56 gamma rays give dramatic proof of nucleosynthesis. In the next issue, the second part of this article will go on to cover the other major triumph – the detection of supernova neutrinos.

Top twenty of the 1980s

What was the hottest particle physics of the past decade? When CERN information specialist David Dallman looked into the high energy physics database to find the most frequently cited papers of the 1980s he found two dominant themes, one theoretical – string theory, and one experimental – the discovery of the W and Z carriers of the weak nuclear force at CERN in 1983.

(The rankings cover only work originating during the 1980s – obviously frequent references were made during the decade to papers written earlier. The results were compiled using the HEPDATA high energy physics information system managed on the CERNVM computer system by the UK Particle Data Group at Durham, which uses the SLAC preprint database.)

The discovery of the W and Z particles at CERN's proton-antiproton collider in 1983 was a watershed in modern science, providing the final rivets for the already solid structure of the electroweak picture – the synthesis of electromagnetism and the weak nuclear force. (Before becoming CERN library's subject specialist, David Dallman had been part of the Vienna team in the UA1 experiment which discovered the W and Z particles in 1983.)

The finding of the W and Z particles by the UA1 and UA2 experiments at CERN were reported in four 1983 Physics Letters, together providing a formidable block of 2254 citations.

With or without big discoveries, the periodic summaries of current information by the international Particle Data Group are well appreciated, the most frequently cited being those in 1986, 1980 and 1988.

The citation rankings show that strings, supersymmetry and related developments became a major industry among theoretical physicists.

Initial efforts to merge the successful electroweak picture with quark forces and with gravity to form a single 'Grand Unified Theory' (GUT) describing everything had been plagued with several major difficulties, notably the vastly different mass scales of the various forces. While electromagnetism and the weak force merge smoothly together at the W and Z mass scale (about 100 GeV), electroweak and quark effects only become comparable at 10^{15} GeV, and gravity has to wait until 10^{19} GeV before it gets an equal vote.

The new ingredient in supersymmetry is to double the number of basic particles – every fundamental quark or lepton gets a supersymmetric field particle counterpart ('squark' or 'slepton'), while the known field particles (photon, W, Z, gluon, graviton) acquire supersymmetric partners (photino, Wino, Zino, gluino, gravitino). With this extra layer of particles, the theory becomes much neater. While no sign of superparticles has yet been found, the search goes on as new machines open up higher energy ranges. Physics Reports review