Abstract

\(\gamma\)-ray bursts have baffled theorists ever since their accidental discovery at the sixties. We suggest that these bursts originate in merger of neutron star binaries, taking place at cosmological distances. These mergers release \(\approx 10^{54}\) ergs, in what are possibly the strongest explosions in the Universe. If even a small fraction of this energy is channeled to an electromagnetic signal it will be detected as a grbs. We examine the virtues and limitations of this model and compare it with the recent Compton \(\gamma\)-ray observatory results.

Prologue: \(\gamma\)-Ray Bursts circa 1973

\(\gamma\)-ray bursts (grbs) were accidentally discovered ahead of their time. Had it not been for the need to verify the outer space treaty of 1967 (which forbade nuclear experiments in space) we would not have known about these bursts until well into the next century. No one would have proposed a satellite to look for such bursts, and had such a proposal been made it would have surely turned down as too speculative. The VELA satellites with omni-directional detectors sensitive to \(\gamma\)-ray pulses, which would have been emitted by a nuclear explosion, were launched in the mid sixties to verify the outer space treaty. These satellites never detected any nuclear explosion. However, as soon as the first satellite was launched it begun to detect puzzling, perplexing and above all entirely unexpected bursts. The lag between the arrival time of the pulses to different satellites gave a directional information and indicated that the sources are outside the solar system. Still, the bursts were kept secret for several years, until Kelbsdal Strong and Olson described them in a seminal paper[1] in 1973.

The unexpected discovery sent theorist in a search for a source model. Specific models ranged from comets to cosmic strings.

False Clues?

The rapid fluctuation in the signal (less than 10ms) suggested a compact source, a neutron star or a black hole. Several other clues focused the attention of theorists towards neutron stars at the disk of the galaxy.

First, came an analytic estimate [2] of the optical depth to \(\gamma\gamma \rightarrow e^+e^-\). For an impulsive source we have:

\[\tau_{\gamma\gamma} \approx \sigma_T F D^2 / R^2 m_e c^2\]

where \(F\) is the fluence (\(\approx 10^{-5} \text{ergs/cm}^2\) in the early detectors and \(\approx 10^{-7} \text{ergs/cm}^2\) in Compton-GRO), \(D\) is the distance to the source and \(R\) its size (expected to be less than \(10^9\) from timing arguments). Since \(\tau_{\gamma\gamma} > 1\) for \(D > 100\)pc, it was argued that the sources must be at
the disk of the galaxy. Otherwise, it was argued an optical thick system will cool down and radiate its energy in the x-ray uv or optical band and not as $\gamma$-rays. The non-thermal spectrum also indicated that the sources are optically thin. Incidentally, it was the confrontation between this argument and the indications from Compton-GRO that grbs are cosmological (which we discuss later) that have lead to claims that grbs require “new physics”. We will see that it ain’t necessarily so.

A very strong and long (1000 sec) burst was observed on March 5th 1979. The position of the burst coincided with a SNR remnant in the LMC supporting the idea that grbs originates on neutron stars.

Another clue came from the observation of absorption lines [3, 4]. The lines were interpreted as cyclotron lines in a $10^{12}$G magnetic field, a field strength that is found only on neutron stars.

These clues and others have led to the consensus that grbs arise on neutron stars in the disk of the galaxy[5], possibly in their magnetosphere.

Bursts distribution circa 1991

There were, however some indications that the sources might not be galactic. In 1975 Usov and Chibisov [6] suggested to use a logN-LogS test to check if the bursts have a cosmological origin. Later, in 1983 van den Bergh [7] analyzed the distribution of the 46 bursts that were known at that time and from the isotropy of this distribution he concluded that the sources are either local at distances of less than half of the galactic disk scale height or cosmological at redshift $z > 0.1$ (See also [3]). The cosmological solution was accepted with skepticism since with typical fluencies of $10^{-5}$ergs/cm$^2$ the bursts require $10^{49}$ergs if they originate at distances larger than 100Mpc! In 1986 Paczyński [4] argued that the bursts are cosmological and suggested that some of the burst are lensed by intervening galaxies and that this will provide an observational test to the cosmological hypothesis. In 1989 Eichler, Livio, Piran and Schramm [10] (see also [11]) suggested that the bursts originate in neutron star mergers at cosmological distances (The possibility that grbs might be produced in neutron star mergers was also mentioned without specifying a model by [12, 3, 13, 4]). However, in 1991, just before the Compton-GRO results were announced, Atteia et al. [15] reported (at a 3$\sigma$ level) that the 244 bursts observed by the spacecrafts Venera 13, 14 and Phebus are concentrated towards the galactic plane, suggesting a disk population after all.

Neutron Star Binaries

Another seemingly unrelated and unexpected discovery was made in 1975 by Hulse and Taylor [16] who found a pulsar, PSR 1913+16, that was orbiting around another neutron star. No one has predicted that such systems exist, but in retrospect it was not surprising. More than half of the stars are in binary systems. If some of these binaries survive the two core collapses (and the supernovae explosions) needed to produce the neutron stars they will end in a binary pulsar.

The binary pulsar have proven to be an excellent laboratory for testing General Relativity. The binary system emits gravitational radiation which is too weak to be detected directly, but its backreaction could be observed. By carefully following the arrival time of the pulsar’s signals Taylor and his collaborator have measured the pulsar’s orbit. They have shown that the binary spirals in just in the right rate to compensate for the energy loss by gravitational radiation emission (with two neutron stars, tidal interactions and other energy losses are negligible). For PSR 1913+16
the spiraling in takes place on a time scale of
\( \tau_{GR} = 3 \times 10^8 \) years, in excellent agreement
with the general relativistic prediction \[17\]. These observations not only confirm the general relativistic prediction, they also assure us that the orbit of the binary is indeed decreasing and that inevitably in \( 3 \times 10^8 \) years the two neutron stars will collide and merge!

Source Count and Event Rate

For many years only one binary pulsar was known. A simple estimate based on the observation of one binary pulsar in several hundred observed pulsars led Clark et al. \[18\] to conclude that about 1 in 300 pulsars is in a binary. With a pulsars’ birth rate of one in fifty years this led to a binary birth rate of one in \( 10^4 \) years. Assuming a steady state, this is also the merger rate. This estimate ignored, however, selection effects in the detection of binary pulsars vs. regular ones. Specifically PSR1913+16 is an extremely bright pulsar which is detectable from much larger distance than an average pulsar. Currently there are four known binary pulsars and an analysis based on their luminosities and life times \[19, 20\] suggests that there are \( \sim 10^4 – 10^5 \) neutron star binaries in the galaxy and that their merger rate is one per \( 10^6 \) years per galaxy. This corresponds to \( \sim 100 \) mergers per year in galaxies out to a distance of 1 Gpc and about \( 10^3 \) per year to the horizon. Narayan, Piran and Shemi \[19\] also predict that a similar or somewhat smaller population of neutron-star black hole binaries will exist.

Neutron Star Mergers

It was immediately realized, after the discovery of PSR1913+16 that the binary produces a unique chirping gravitational radiation signal during the last seconds before the neutron stars merge. These signals are probably the best candidates for detection of gravitational radiation. However, these events are rare and to observe them (gravitationally) in our life time we must turn to extragalactic events. This is the aim of the advanced gravitational radiation detectors like LIGO \[21\].

As the strongest sources of gravitational radiation neutron star mergers attracted the attention of relativists, but most astronomers ignored them as being too rare to be of interest. Clark and Eardley \[22\] have shown that the binding energy released in a neutron star binary merger is \( \sim 5 \times 10^{53} – 10^{54} \text{ergs} \), making these events possibly the most powerful explosions in the Universe. A significant fraction of this energy is emitted as gravitational radiation, both prior and during the collision. A very sophisticated gravitational radiation detector, LIGO, is built to detect these gravitational radiation signals. But it will be around the turn of the century when it is operational.

As the neutron stars collide a shock forms and the stars heat up. Most of the binding energy is emitted as neutrinos \[22\]. The neutrino burst is comparable or slightly stronger than a supernova neutrino burst (such as the one detected by Kamiokande and IMB from 1987A). To detect extragalactic events at cosmological distances we need a detector which is \( \approx 10^8 \) times larger than those detectors. With regular supernova neutrino bursts being a hundred times more frequent it is clear that these neutrino signals are not the prime candidates for detection.

Neutron star mergers are hiding from us by emitting their energy in two channels with extremely small cross sections. If even a small fraction of the energy is channeled to an electromagnetic signal, its much large cross section will make it much easier to observe. For many years, I kept wondering what are the possible observational consequences of such events \[14\].
Energy Conversion

Goodman, Dar and Nussinov [14] suggested that the neutrino-antineutrino annihilation $\nu + \bar{\nu} \rightarrow e^+ + e^-$ converts a small fraction of the neutrino supernova burst to electron-positron pairs which in turn annihilate to $\gamma$-rays, heat the surrounding envelop and provide the energy required to power the supernova shock wave. In 1989, Eichler, Livio, Piran and Schramm [10] (see also [11]) suggested that the same mechanism operates in neutron star mergers and converts $\sim 10^{-3}$ of of the emitted energy to pairs and $\gamma$-rays. This corresponds to $10^{51}$ ergs, roughly sufficient for detection of the bursts from cosmological distances. Eichler et al. [10] used the old estimate of Clark et al. [18] for the merger rate and suggested that these events would be detected by Compton observatory as grbs.

More recently, alternative energy generation mechanism such as magnetic field recombination [23] or accretion onto the neutron star [24] have been proposed and it was argued that they provide comparable amounts of energy.

Fireballs and Relativistic Effects

If grbs are indeed cosmological they are initially optically thick, as Schmidt [2] have argued. How can there be a $\gamma$-ray burst from such a source? Goodman [13] considered a dense sphere of $\gamma$-ray photons and pairs, which he called a fireball. He has shown that as long as the fireball is optically thick the radiation-pair plasma will behave like a fluid with $p = \rho/3$. The fireball will expand and cool, just like the early Universe (unlike our Universe the gravitational force is unimportant). As the fireball cools its temperature drops with $T \propto 1/R$ until the electron positions annihilate (the annihilation is complete at $T \approx 20$ keV) and the radiation escapes. The radiation fluid has reached in the meantime a relativistic velocity relative to an observer at infinity and its Lorentz factor $\Gamma \approx R_{esc}/R_0 \approx T_0/T_{esc} \approx 10^3 - 10^4$. The escaping photons, which have a typical energy of 20 keV in the local frame are blue shifted relative to an observer at infinity and their observed energy is $E_{obs} \approx \Gamma T_{esc} \approx T_0$, of the same order as the initial energy. In this way the optical depth argument which limited the distances to the sources is bypassed and there is no need to introduce “new physics” to explain grbs from cosmological distances.

Paczyński [9] have shown that similar effects take place if the radiation is released in a quasi-stationary manner. In this case the radiation flows out as a relativistic wind, with $T \propto 1/R$ and $\Gamma \propto R$. The radiation ceases to behave like a fluid and escapes when $T \approx 20$ keV in the local frame. The escaping x-ray photons are blueshifted to much higher energies in the observer frame.

Do Fireballs Work?

The fireball model faces two serious objections: the origin of the observed nonthermal spectrum and the effects of baryons.

There is no clear way to explain the nonthermal spectrum from a fireball that passes an optically thick phase and termalizes. It is possible that different regions in a realistic, inhomogeneous fireball move with significantly different Lorentz $\Gamma$ factors and that the observed spectrum is a blending of thermal spectra to a non thermal one. Simple calculations of the spectrum of a spherical fireball [25] show some deviation from a thermal spectrum, but it is not large enough. Alternatively one could hope that the spectrum would become nonthermal in the transition from optically thick to optically thin regimes. However, this transition takes place at $\approx 20$keV in the local frame. The energy injected from annihilation at this stage is insignificant and the temperature is too low for inverse Compton scattering to be
effective. It seems that there is no clear mechanism that will modify the photons’ black body spectrum in this stage.

One expects that some baryons will be ejected into the fireball. Shemi and Piran have shown that the baryons have two effects. For \(10^{-11}M_\odot < M < 10^{-8}M_\odot(E_0/10^{51}\text{ergs})\) the baryons dominate the opacity (long after all the pairs have annihilated) without influencing the fireball’s inertia. The fireball continues to be optically thick until \(\tau_g = \sigma_T M/R^2 = 1\). This leads to a longer acceleration phase and to a larger final Lorentz factor \(\Gamma_f \approx R/R_0 \approx T_0/T\). However, the final energy of the escaping radiation remains unchanged with \(\epsilon \approx \Gamma T \approx T_0\).

Larger baryonic load changes the dynamics of the fireball. As the fireball expands \(\rho \propto R^{-3}\) while \(e \propto r^{-4}\). If \(M > 10^{-8}M_\odot(E_0/10^{51}\text{ergs})\) the baryonic rest mass will dominate the energy density and the fireball’s inertia before the fireball becomes optically thin. In these cases all the energy will be used to accelerate the baryons with \(E_K = Mc^2\Gamma \approx (E_0 + Mc^2)/(E_0T/Mc^2T_0 + 1)\). The final outcome of a loaded fireball will be relativistic expanding baryons with \(\Gamma \approx E_0/Mc^2\) and no radiation at all.

Several ideas have been proposed to avoid the baryonic load problem. These include: (i) Separation of the radiation and the baryons due to deviations from spherical symmetry - the radiation escaping along the axis and the baryons being ejected preferably in the equatorial plane and (ii) generation of a radiation fireball with very small amounts of matter via magnetic processes.

Energy Conversion, Once More

If the baryonic contamination is in the range \(10^{-5}E_0 < Mc^2 < 0.1E_0\) all the initial fireball energy will be converted to extremely relativistic protons moving at a Lorentz fac-

tors \(10 < \Gamma \approx E_0/Mc^2 < 10^5\). Recently Mészáros, and Rees (see also [23]) suggested that this energy could be converted back to \(\gamma\)-rays when this baryons interact with the surrounding interstellar matter. A shock, quite similar to a SNR shock, forms and it cools predominantly via synchrotron emission in the x-rays. The x-ray photons will be blueshifted to \(\gamma\)-rays in the observer frame due to the relativistic velocity of the fireball. The relativistic motion will also lead to a short time scale for the burst. Alternatively, the accelerated baryons could interact with a pre-merger wind that surrounds the fireball [23, 20]. In both cases the interaction with the surrounding material will lead once more to the conversion of the energy: from kinetic energy back to radiation. Since this phase is taking place in an optically thin region the photons will not thermalize and the emerging spectra will be non thermal, as observed. Thus, this process seems to resolve at one stroke both major objections to the fireball scenario at one stroke.

\(\gamma\)-ray bursts distribution circa 1992

The Compton \(\gamma\)-ray observatory was launched in the spring of 1991 (see [30] for a review). It includes an omnidirectional \(\gamma\)-ray burst detector (BATSE) which, with a limiting sensitivity of \(\approx 10^{-7}\text{ergs/cm}^2\), is the most sensitive detector of this kind flown. By the summer of 1992 BATSE has detected more than 400 bursts, more than all previous detectors combined. BATSE is also capable of obtaining a directional information on the bursts on its own. Within four month from its launch BATSE has collected enough data to conclude that the distribution of grbs sources is isotropic [31]. When the \(V/V_{\text{max}}\) test was applied to the burst intensity distribution it was shown that the sources are not distributed homogeneously in space and that there is a concentration of sources towards us [31].
These two observations rule out all local galactic disk models. The observations are consistent with three possible populations: (i) Cosmological population (ii) Galactic halo population with a large core radius (> 50 kpc) and (iii) A population, such as comets at the Oort cloud, centered around the solar system.

We will turn to the second and third possibilities, before summing up the status of the cosmological population models.

**Galactic Halo models**

Galactic Halo models require a halo population with a large core radius (to avoid an anisotropic enhancement towards the galactic center). This is a new population of astronomical objects, which was not seen elsewhere [24]. It probably requires a different distribution (in space) than the dark halo material (the latter being too concentrated towards the galactic center). By now there have been several suggestions how to form a neutron population of this kind. These include either ejection from the galactic disk or formation in situ. However, these models face additional difficulties.

Approximately $10^{41}$ ergs are needed for bursts at the halo, quite a large amount for a neutron star. With a typical size of $10^6$ cm this leads to an optical thickness of $\approx 10^8$ for $\gamma \gamma \rightarrow e^+e^-$. These constraints have two far reaching implications: First, the optically thin neutron star models suggested for galactic disk sources are inapplicable to grbs at the halo. Second, galactic halo sources inevitably involve an opaque pair plasma fireball, just like cosmological sources [32]. The physical conditions in these fireballs are, however, less favorable than the conditions at cosmological fireballs for production of grbs.

**Local Population**

Typical objects in the solar system have a very small binding energy per baryon and it is difficult to imagine a mechanism in which such objects generate energies in the $\gamma$-ray range (see however [33]). The only hope is probably via a magnetic phenomenon. Solar flares do generate grbs which are detected by Compton-GRO (these are identified by their location and spectrum [34]). However, comparison of the size and masses involved in these events make it inconceivable that similar conditions can be achieved elsewhere in the vicinity of the solar system, without leaving any other trace.

**Cosmological Population**

Several groups [35, 36, 37, 38] have shown that a cosmological population is compatible with the observed $V/V_{max}$ distribution. The apparent concentration towards us is an artifact of a combination of redshift effects and a possible cosmological evolution. Unfortunately it is impossible to separate the two effects and to determine the typical red shift, $\langle Z \rangle$, to the sources from the $V/V_{max}$ distribution. Depending on the cosmological model and the source evolution we have $0.3 < Z_{av} < 3$. For $\Omega = 1$ and no evolution $Z_{av} \approx 1$ [36].

The event rate needed to explain the observation is in an amazing agreement with the rates estimated for neutron star mergers [19, 20]. Because of a historical coincidence the forth binary pulsar, PSR1534+12, which played a decisive role in the determination of the merger rate [19, 20], was discovered [39] a few month before Compton-GRO was launched and the prediction of the neutron star merger rate were not influenced by the rates required to explain the Compton-GRO results.

Several other cosmological grbs models were suggested after Compton-GRO [40, 41, 42, 43]. Within the cosmological framework, the neutron star merger scenario is the most conservative one possible. It is the only one
based on a source population that definitely exists. We know its members will merge, we can be certain that huge quantities of energy will be released in such mergers, and we find the merger rate to be comparable to the observed burst rate.

Clues Revisited

Before concluding we turn once more to the clues discussed earlier. The optical depth problem disappeared in some sense and remained in another. Relativistic effects, due to the expansion of the fireball [13, 9], were not taken into account in the original argument [2] which is flawed. The resulting spectrum from the expanding fireball has the right energy range but to a first approximation it is thermal. It is a non-trivial (but not impossible) task to obtain a nonthermal spectrum. This problem is shared by all cosmological and galactic halo models.

The March 5th event was one of three soft γ-ray repeaters, which have a softer spectrum and produce repeated bursts from the same source, unlike all other sources [3]. It is by now generally accepted that these are most likely a different phenomenon.

The nature of the cyclotron lines has been fairly controversial since they were first reported [44, 45]. Mazets etal. [3] claimed that single “cyclotron absorption lines” were present in 20 bursts, with a broad distribution of line energies (27–70 keV), but with only five lines having energies under 50 keV. This is in conflict with the GINGA experiment which discovered three systems of lines, all with nearly identical energies, all under 50 keV [4]. So far, no lines have been detected with any experiment on the Compton Gamma Ray Observatory.

Epilogue: γ-ray bursts circa 2000

A general test for all cosmological models is the expected positive correlation between the faintness of a burst (correlated with distance) and redshift signatures through the burst duration and spectrum [16, 19]. This correlation could be masked by large intrinsic variations among bursts, but should eventually be observed when enough data accumulate.

At present there are no known optical counterparts to grbs. Since neutron star binaries might be ejected from dwarf galaxies, we predict [23], that grbs occur within a few tens of arcsecond from dwarf galaxies and within but not necessarily at the center of ellipticals. Optical identification of some parent galaxies, could support this model and the location of the burst relative to the galaxy could distinguish this model from other cosmological scenarios that involve supermassive black holes or other objects located in the centers of galaxies [10, 12, 11].

The scenario makes one unique prediction: strong γ-ray bursts should be accompanied by a gravitational wave signal [28, 36, 23] (though the reverse need not necessarily be true if the γ-rays are beamed). These signals should be detected by LIGO [21] when it becomes operational (hopefully by the year 2000). LIGO should provide good distance estimates to individual bursts [17] and should also pinpoint the exact time of the merger, in addition to furnishing an ultimate proof of this model.

REFERENCES

[1] R. W. Klebesedal, I. B. Strong, and R. A. Olson, Ap. J. L., 182, L85, 1973.
[2] Schmidt, W. K. H., 1978, Nature, 271, 525.
[3] Mazet E. P. etal. , 1981, Nature, 290, 378.
[4] Yoshida, A., etal. 1992, PASJ, 43, in press.
[5] Higdon, J. C., and Lingenfelter, R. E. 1990, *Ann. Rev. Astron. Astrophys.*, 28, 401.

[6] Usov, V. V. and Chibisov, G. V. 1975, *Soviet Astr.*, 19, 115.

[7] van den Bergh, S. 1983, *Astrophys. and Space Sci.*, 97, 385.

[8] Hartman, D. and Blumenthal, G. R., 1989, *Ap. J.*, 342, 521.

[9] Paczyński, B., 1986, *Ap. J. L.*, 308, L51.

[10] Eichler, D., Livio, M., Piran, T., and Schramm, D. N. 1989, *Nature*, 340, 126.

[11] Piran, T., 1990, in Wheeler, J. C., Piran, T. and Weinberg, S. *Supernovae* World Scientific Publications.

[12] Blinikov, S., I., et al., 1984, *Sov. Astron. Lett.* 10, 177.

[13] Goodman, J., 1986, *Ap. J. L.*, 308 L47.

[14] Goodman, J., Dar, A. and Nussinov, S. 1987, *Ap. J. L.*, 314, L7.

[15] Atteia, J. L., et al. 1991, *Nature*, 351, 296.

[16] Hulse, R. A., and Taylor, J. H., 1975, *Ap. J.*, 368, 504.

[17] Taylor, J. H. and Weisberg R. M., 1989, *Ap. J.*, 345, 434.

[18] Clark, J. P. A, van den Heuvel, E. P. J., and Sutantyo, W., 1979, *Astron. and Astrophys.*, 72, 120.

[19] Narayan, R., Piran, T. and Shemi, A., 1991, *Ap. J. L.*, 379, L17.

[20] Phinney, E. S., 1991, *Ap. J. L.*, 380, L17.

[21] Abramovici, W. E. et al. 1992, *Science*, 256, 325.

[22] Clark, J. P. A., and Eardley, D., 1977, *Ap. J.*, 215, 311.

[23] Narayan, R., Paczyński, B., and Piran, T., 1992, *Ap. J. L.*, 395, L83.

[24] Paczyński, B., 1992, in *30*, 144.

[25] Shemi, A., Piran, T., and Narayan, R., 1992, in preparation.

[26] Narayan, R., Piran, T., and Yi, I., 1992, in preparation.

[27] Shemi, A. and Piran, T., 1990, *Ap. J. L.*, 65, L55.

[28] Piran, T., Narayan, R. and Shemi, A., 1992, in *30*, 149.

[29] Mészáros, P. and Rees, M.J., 1992, *Ap. J.*, in press.

[30] Paciesas W. S. and Fishman, G. J. 1992, eds. *Gamma-Ray Burst, Huntsville, 1991*, AIP press.

[31] Meegan, C.A., et al. , *Nature*, 355 143.

[32] Piran, T. and Shemi, A., 1992, *Ap. J. L.*, in press.

[33] Katz, J. I. 1992, preprint.

[34] Fishman, G. J. et al. , 1992, in *30*, 94.

[35] Mao, S. and Paczyński, B. 1992, *Ap. J. L.*, 388, L45.

[36] Piran, T., 1992, *Ap. J. L.389*, L45.

[37] Dermer, C. D. 1992, *Phys. Rev. Letters*, 68, 1799.

[38] Schmidt, M. 1992, in *31*.

[39] Wolszczan, A., 1991, *Nature*, 350, 688.

[40] Carter, B. 1992, preprint.

[41] Hoyle, F. and Burbidge, G. 1992, *Proc. European Sp. Yr. Conf.: Symp. 3 – High Energy Astrophysics*, in press.

[42] McBreen, B., Plunkett, S. and Metcalfe, L. 1992, preprint.

[43] Usov, V. V., 1992, *Nature*, 357, 472.

[44] Laros, J. G., et al. 1982, *Astrophys. Space Sci.*, 88, 243.

[45] Harding, A. K., Petrosian, V., and Teegarden, B. J. 1986, in *Gamma-Ray Bursts*, Eds: E. P. Liang and V. Petrosian, p. 75.
[46] Paczyński, B. 1992, *Nature*, 355, 521.

[47] Schutz, B. 1986, *Nature*, 323, 310.