source and background according to the occultations of the new position. If the observed line flux is actually due to emission from SN1987A, the measured flux at a different assumed position will depend only on the relative exposure to the supernova in the source and background spectra for that position. Figures 3 and 4 show the fitted fluxes for positions differing in right ascension and declination from that of the supernova. Also shown are the expected fluxes based on exposure. In both cases the data are in good agreement with the supernova exposure. Note however that the data points are not independent, so the error bars are misleading. The variations of intensities of apparent background features in the spectrum do not agree well with the model.

We have looked for a second strong line of ^{56}Co decay at 1,238 keV. Based on the branching ratio, the 1,238 keV line should be present with at least 67.9% of the 847-keV flux, or 6.8×10^{-4} photons cm^{-2} s^{-1}. If there is significant attenuating material above the ^{56}Co, this flux should be higher, perhaps exceeding that of the 847 keV line (see discussion below). Imperfect subtraction of the lines from the internal calibration sources may leave positive or negative features at 1,173 and 1,333 keV. These are visible in the two spectra in Fig. 2. Fitting the 1,238-keV line simultaneously with the residual background lines gives a flux of $(6\pm2)\times10^{-4}$ photons cm^{-2} s^{-1} at $1,218\pm16$ keV. This intensity is consistent with the lowest expected flux. We have applied the systematic check using test positions described above to the 1,238-keV line. The 1,238-keV line intensity variations agree with those expected for emission from the supernova. However, both the statistics and the systematics make this result less certain than the detection of the 847-keV line.

The fluxes in these lines are equivalent to what would have been observed during this period if there were $\sim2.3\times10^{-4}$ M of totally exposed ^{56}Co present at 55 kpc on 1 August. This is only ~1.3% of the total mass of ^{56}Co thought to be present in the supernova ejecta at that time, based on the light curve[4,5]. This suggests that the observed gamma rays may have been produced by a small fraction of the total ^{56}Co under very little material, or by all the ^{56}Co under a thick attenuating envelope. Since 847-keV photons are more likely to scatter than 1,238-keV photons, a thick envelope will enhance the 1,238-keV flux with respect to that at 847 keV. The observed line ratio is $F_{1,238}/F_{847} = 0.60\pm0.25$, consistent with the laboratory branching ratio of 68%. This places a limit on the thickness of the material above the ^{56}Co. If the observed gamma-ray lines were produced by the total mass of ^{56}Co under a thick attenuating envelope, the overlying material would have to have an average effective optical depth of $\tau_{847}\approx4$ to reduce the 847-keV flux to the measured intensity. A Monte Carlo calculation[9] indicates that an envelope this thick would produce a line ratio of 1.1, which is unlikely, but not excluded by the data. Another problem with this model is that some of the scattered gamma rays will emerge as X-rays, and the calculated hard X-ray flux is about ten times that actually observed by MIR[6,9].

Alternatively, the observed gamma rays may have been produced by a small fraction of the total mass of ^{56}Co under very little material. Such a situation might arise in the supernova if the envelope is non-uniform, or if a small amount of ^{56}Co has moved or been mixed out beyond the bulk of the ejecta. In this case, the measured line ratios will be close to the branching ratio. In addition, the mass of material overlying the observed ^{56}Co can be chosen to make the gamma-ray fluxes consistent with the observed hard X-rays. This would, however, produce a spectrum somewhat harder than is observed[9]. It is interesting to note that one explanation proposed for the luminosity of the mysterious "companion" of the supernova requires that a similar mass of ^{56}Co be expelled as a blob or jet[10,11].

The GRS has observed a line at an energy consistent with 847 keV in the background-subtracted spectra for SN1987A for over 80 days. No previously observed statistical or systematic fluctuations can explain this feature. We conclude that this line is probably due to the decay of ^{56}Co in the supernova ejecta. Although we cannot absolutely rule out that this is the first appearance of a new and unexpected background effect, we believe that this is unlikely to be the case. There is also evidence for the presence of the 1,238-keV decay line. The line fluxes do not appear to have risen since the initial detection. The best fit to the data indicates that the flux is slowly declining, but the data are consistent with a wide range of models, including a constant or slowly rising intensity. Based on the best fit to the time history since August, we would predict that the balloon experiments launched last autumn would have seen a flux of roughly $(3\text{-}7)\times10^{-4}$ photons cm^{-2} s^{-1} in the 847 keV line. GRS observations of SN1987A are continuing.

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1. Clayton, D. D., Colgate, S. A. & Fishman, G. J. *Astrophys. J.* **155**, 75-82 (1969).
2. Bodansky, D., Clayton, D. D. & Fowler, W. A. *Astrophys. J. Suppl. Ser.* **16**, 299-371 (1968).
3. Colgate, S. E. & McKee, C. *Astrophys. J.* **157**, 623-643 (1969).
4. Catchpole, R. M. *et al. Mon. Not. R. Astr. Soc.* (submitted).
5. Woosley, S. E. *Astrophys. J.* (submitted).
6. Sunyaev, R. *et al. Nature* **330**, 227-230 (1987).
7. Dotani, T. *et al. Nature* **330**, 230-231 (1987).
8. Forrest, D. J. *et al. Solar Phys.* **65**, 15-23 (1980).
9. Leising, M. D. *Nature* (submitted).
10. Goldman, I. *Astr. Astrophys.* **186**, L3-L4 (1987).
11. Piran, T. & Nakamura, T. *Nature* **330**, 28 (1987).

Observation of an ionospheric disturbance caused by a gamma-ray burst

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We report a first observation of an ionospheric disturbance from a gamma-ray burst. The burst, GB830801, occurred at 22:14:18 UT on 1 August 1983 and was one of the strongest ever observed. The total fluence was 2×10^{-3} erg cm^{-2}, most of which occurred in the first 4 s of the burst. Simultaneously, a change was observed in the amplitude of a very-low-frequency (VLF) radio signal from a transmitter in Rugby, England, monitored at Palmer Station, Antarctica, indicative of an ionospheric disturbance. Weaker disturbances were also recorded at the same receiving site on signals from VLF stations in Annapolis, Maryland and Lualualei, Hawaii. The times of the burst and the disturbances are coincident within the 10-s resolution of the VLF recording system. No similar disturbances were observed within 60 h around the time of the burst. In the future, a network of VLF burst monitors may provide

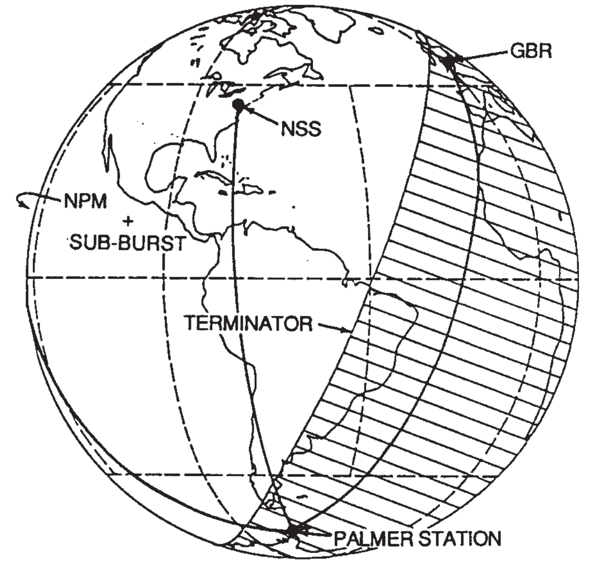

Fig. 1 The great-circle paths of the three VLF signals are shown along with the location of the sunset terminator at the time of the gamma-ray burst. The sub-burst position is indicated by a cross.

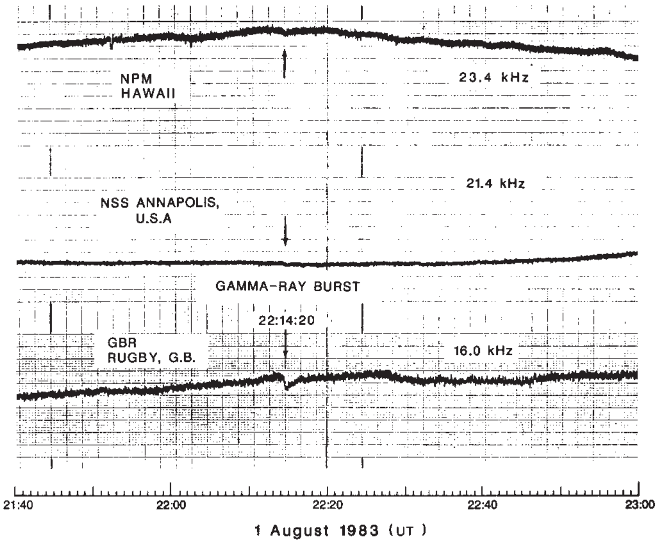

Fig. 2 Amplitude (arbitrary units) of the VLF radio signals received at Palmer, Antarctica from the three stations indicated. The ionospheric disturbances at the time of the gamma-ray burst are indicated by arrows.

measurements of the total ionizing energy fluence from a burst, as well as some limited directional information.

VLF radio propagation is a sensitive probe of the lowest portions of the ionosphere, from 40 km to 90 km[1]. In this region cosmic rays provide the major source of ionization. VLF radio signals travel long distances with little attenuation and their propagation is best modelled by wave-guide mode theory[2,3]. High-power continuous VLF radio transmissions are used by several countries for global navigation and communication. An enhancement of ionization in the lower ionosphere can be detected as an amplitude change or a phase shift of the received VLF signal. The magnitude and the sign of the amplitude change are dependent on the transmitter-receiver path, the VLF frequency and the altitude profile of the ionization change[4,5].

In several fields of research, VLF propagation has been used to monitor transient ionospheric enhancements (disturbances). For many years, solar flares have been observed through sudden ionospheric disturbances[6] (SIDs). Monitoring distant VLF radio signals has been shown to be one of the most sensitive indicators of hard X-ray and microwave emission from flares[6-10]. Bain and Hammon[10], for example, noted the success in detecting solar flares by VLF-phase-anomaly monitoring for solar X-ray flares with peak intensity $>6\times10^{-4}$ erg cm^{-2} s^{-1} (3-20 keV). A threshold for detection of 2×10^{-3} erg cm^{-2} s^{-1} was reported by Kreplin *et al.*[7]. VLF propagation studies are also used as probes of sporadic electron precipitation caused by disturbances in the Earth's magnetosphere[4,5,11-15]. One type of transient precipitation is believed to be induced by whistlers which, in turn, are generated by strong lightning discharges[16-18]. The monitoring of VLF propagation has also been used to study the effects on the ionosphere of strong X-ray sources such as Sco X-1, Cyg X-3, Cen X-2 and Cen X-4, but the results have been unconfirmed[19-24]. Hudson and TeKolste[25] have suggested monitoring VLF propagation to detect pulsed ionization enhancements from strong X-ray pulsars such as A0535+26 and the Crab Pulsar.

The effects of a gamma-ray burst on the ionosphere were first calculated by Brown[26]. Others have also published calculations of the ionization profiles expected from gamma-ray bursts[23,28-30]. These calculations show that the peak of the ionization due to a gamma-ray burst takes place in the region from 25 km to 35 km, but significant ionization occurs, primarily from Compton electrons, up to what is usually considered the night-time reflection height for VLF propagation, ~85 km[27].

The observations reported here were obtained with apparatus normally used to observe the relationships between whistlers and their effects on VLF propagation[16]. The receiving station was located at the Palmer Station, Antarctica (65° S, 64° W). An analog strip chart recorder monitored various sources of data relevant to the magnetospheric studies, with a time resolution of about 10 s. Three channels consisted of the amplitude of the received signal from distant VLF transmitters (Fig. 1). Some properties of the transmitters and the propagation distances are given in Table 1.

Figure 2 shows a portion of the record from the three stations between 21:40 UT and 23:00 UT on 1 August 1983. A clear indication of a disturbance beginning at 22:14:10 ± 10 UT is seen in the radio station GBR signal. Weaker, barely detectable decreases in amplitude are seen simultaneously in the two other signals. Without the GBR signal, these other two signals alone would have been considered uneventful as similar weak fluctuations are seen in their records near the time of the burst. The disturbance in the GBR signal differs in its rise-and-fall time from any other disturbances seen within 60 h of the burst. The GBR disturbance has a rise time of <20 s and returns to the

Table 1 VLF transmission paths

Station	Location	Frequency (kHz)	Latitude	Longitude	Path to Palmer, Antarctica Arc length	Distance ($\times10^6$ m)
GBR	Rugby, UK	16.0	52°24′ N	01°12′ W	127°	14.1
NPM	Lualuaiei, Hawaii	23.4	21°25′ N	158°09′ W	107°	11.9
NSS	Annapolis, USA	21.4	38°59′ N	76°27′ W	105°	11.6

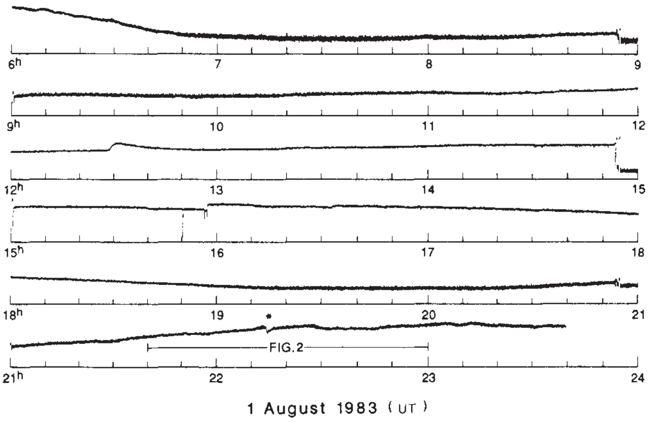

Fig. 3 Extended record (18 h) of the 16-kHz signal from station GBR. A more typical solar-type disturbance is seen at 12:40 UT, having a longer rise and fall time than the disturbance due to the gamma-ray burst at 22:14 UT. Other sudden jumps in the record are due to adjustments in the transmitter or in the receiving equipment. The time of the gamma-ray burst is indicated by a star.

pre-disturbance baseline in ~200 s. A 16-h sample of the GBR signal is shown in Fig. 3.

The gamma-ray burst at 22:14:20 UT, 1 August 1983 (GB830801), was observed by the Signe-2MP9 experiment on the Prognoz-9 satellite[31,32], by the International Comet Explorer[33] (ICE) and by the Vela spacecraft (J. Laros, personal communication). The burst was one of the strongest recorded to date, with a total energy fluence of at least 2×10^{-3} erg cm^{-2} (ref. 31). It was observed over the energy range from 5 keV to 7.5 MeV. In addition to its intensity, the burst was unusual because of its smooth time profile. The higher energy radiation rose to near maximum in 1 s, then dropped to ~15% of the peak in 5 s. The lower energy radiation lasted for >40 s (ref. 33).

The observed ionospheric disturbance is attributed to the gamma-ray burst GB830801 due to its temporal coincidence and the fact that solar X-ray flares of this intensity level are observed to produce disturbances of similar magnitude[6,10]. An important distinction between solar flares and gamma-ray bursts is that the typical flare duration is longer and the mean photon energy is lower. Furthermore, recent quantitative models of ionization due to sporadic electron precipitation and its effect on VLF radio propagation would support the hypothesis that a gamma-ray burst with a total energy of 10^{-3} erg cm^{-2} would produce the observed effect[4,5].

The gamma-ray burst location was derived from timing measurements from three widely separated spacecraft: ICE, Prognoz and Vela. The most likely location was RA = 11 h 48 min, dec. = +13°, in the constellation Leo, with an error radius of ~5° (J. Laros, personal communication). At the time of the burst, the point on the Earth directly beneath the burst (sub-burst point) was 103° W longitude +13° S latitude, ~800 km southwest of Guatemala. Fortuitously, all three of the transmission paths (Fig. 1, Table 1) were entirely within the hemisphere of the Earth that was irradiated by the burst. The path from Rugby to Palmer, Antarctica, was 65° to 85° from the sub-burst point, and the other two transmission paths were considerably closer. The fact that the disturbance measured by the GBR signal was greater than that of the other two signals may be due to this signal path occurring almost entirely during night-time. The VLF reflection height for a night-time ionosphere is typically at ~85 km (ref. 27). If the amplitude change is due to increased absorption, then a night-time path would allow the signal to traverse a region of greater integrated ionization. At the time of the burst, no solar activity was reported in the radio or microwave region[34].

There are several possible uses for the observation of gamma-ray bursts through ionospheric disturbances. It may be possible to localize better some burst directions through a large network of observations. Although the zenith angle dependence of ionization due to a burst is rather small[26], observations from a network of various path lengths could indicate the fraction of the paths that are in the irradiated hemisphere of the burst. For other observing conditions being equal, the magnitude of the disturbance should be proportional to the path length affected by the burst. These observations could also yield the total ionizing fluence of a gamma-ray burst. This measurement is difficult to obtain from spaceborne observations due to the limited energy range of the detectors used for gamma-ray burst observations and because of detector saturation in the observation of the strongest bursts. For those bursts which can be measured by both space-borne and VLF techniques, they would provide a calibration of the magnitude of VLF propagation disturbances from known ionizing sources (M. Walt, personal communication). These data would be important for continuing studies of magnetospheric-ionospheric coupling processes.

Based on the known log N-log S distribution of strong gamma-ray bursts[35] (spectral index = −1·5), and assuming that the observed signal was about five times the minimum detectable signal, then only a few gamma-ray bursts per year can be studied through ionospheric disturbances. However, coincidence techniques and a network of receiving sites could considerably improve the observability of burst-induced disturbances.

As a final note of interest, this may be the first time that a transient extra-solar phenomenon has measurably affected a part of the Earth's environment.

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1. Sechrist, C. S. Jr *Radio Sci.* **9**, 137-149 (1974).
2. Watt, A. D. *VLF Radio Engineering* (Pergamon, Oxford, 1967).
3. Kikuchi, T. *J. atmos. terr. Phys.* **48**, 15-23 (1986).
4. Tolstoy, A., Rosenberg, T. J., Inan, U. S. & Carpenter, D. L. *J. geophys. Res.* **91**, 13473-13482 (1986).
5. Tolstoy, A. *thesis* Univ. Maryland (1983).
6. Mitra, A. P. *Ionospheric Effects of Solar Flares* (Reidel, Dordrecht, 1974).
7. Kreplin, R. W., Chubb, T. A. & Friedman, H. *J. geophys. Res.* **67**, 2231-2253 (1962).
8. Kaufmann, P. & Paes de Barros, M. H. *Sol. Phys.* **9**, 478-486 (1969).
9. Kaufmann, P. & Rizzo Piazza, L. *Sol. Phys.* **57**, 479-481 (1978).
10. Bain, W. C. & Hammon, E. *J. atmos. terr. Phys.* **37**, 573-574 (1975).
11. Potemra, T. A. & Rosenberg, T. J. *J. geophys. Res.* **78**, 1572-1580 (1973).
12. Westerlund, S. & Reder, F. H. *J. atmos. terr. Phys.* **35**, 1453-1474 (1973).
13. Helliwell, R. A., Katsufrakis, J. P. & Trimpi, M. L. *J. geophys. Res.* **78**, 4679-4688 (1973).
14. Muraoka, Y. *J. atmos. terr. Phys.* **41**, 1031-1042 (1979).
15. Kikuchi, T. & Evans, D. S. *J. geophys. Res.* **88**, 871-880 (1983).
16. Inan, U. S., Carpenter, D. L., Helliwell, R. A. & Katsufrakis, J. P. *J. geophys. Res.* **90**, 7457-7469 (1985).
17. Inan, U. S. & Carpenter, D. L. *J. geophys. Res.* **92**, 3293-3303 (1987).
18. Goldberg, R. A., Barcus, J. R., Hale, L. C. & Curtis, S. A. *J. atmos. terr. Phys.* **48**, 293-299 (1986).
19. Ananthakrishnan, S. & Ramanathan, K. *Nature* **223**, 488-489 (1969).
20. Svennesson, J. & Westerlund, S. *J. atmos. terr. Phys.* **41**, 361-365 (1969).
21. Svennesson, J., Reder, F. & Crouchley, J. *J. atmos. terr. Phys.* **34**, 49-72 (1972).
22. Kaufmann, P., Piazza, L. R. & Ananthakrishnan, S. *Astrophys. Space Sci.* **22**, 67-70 (1973).
23. Kasturirangan, K., Rao, U. R., Sharma, D. P., Rastogi, R. C. & Chakravarty, S. C. *Astrophys. Space Sci.* **42**, 57-62 (1976).
24. Rizzo Piazza, L., Kaufmann, P. & Ramirez Pardo, P. *J. atmos. terr. Phys.* **45**, 121-125 (1983).
25. Hudson, H. & TeKolste, R. *Bull. Am. astr. Soc.* **16**, 982 (1984).
26. Brown, R. T. *Nature* **246**, 83-84 (1973).
27. Deeks, D. G. *Proc. R. Soc.* Ser. A, **291**, 413-425 (1966).
28. Baird, G. A. *J. atmos. terr. Phys.* **36**, 1565-1569 (1974).
29. O'Mongain, E. & Baird, G. A. *Astrophys. Space Sci.* **42**, 63-67 (1976).
30. Weekes, T. C. *J. atmos. terr. Phys.* **38**, 1021-1026 (1976).
31. Kuznetsov, A. V. *et al. Sov. Astr. Lett.* **12**, 315-318 (1986).
32. Boer, M. *et al. Adv. Space Res.* **6**, 97-102 (1986).
33. Laros, J. in *Gamma Ray Bursts* (eds Liang, E. P. & Petrosian, V.) 84-86 (AIP Press, New York, 1986).
34. *Solar-Geophysical Data No. 474 Part II*, 6 (NOAA, Boulder, 1984).
35. Mazets, E. *et al. Astrophys. space Sci.* **80**, 3-83 (1981).