9. P. J. McGovern, C. B. Siren, S. C. Solomon, unpublished material.
10. E. R. Stofan *et al.*, *J. Geophys. Res.* **97**, 13347 (1992). We modified the original database by removing four entries and adjusting the maximum widths of five features on the basis of Magellan images.
11. G. H. Pettengill, P. G. Ford, W. T. K. Johnson, R. K. Raney, L. A. Soderblom, *Science* **252**, 260 (1991). C1- and F-MIDRs are compressed-once and full-resolution Magellan image data records, respectively. Where the edges of lava flows are not clear in standard images, we applied high-pass and median filtering to measure flow area.
12. V. L. Sharpton, *Eos* **73** (fall meeting suppl.), 331 (1992). We have assumed an ejecta width that is 0.4 of the crater diameter.
13. On the basis of a χ^2 test, the probability that the two distributions are identical is 0.02%; the probability that the two are the same except for a scaling factor is 74%.
14. The average crater retention age of the surface on Venus has been estimated to lie between 210 and 720 My (*2*) and between 400 and 800 My (*3*). We take 500 My as a representative value (*2, 3*). The areal resurfacing rate and volcanic flux scale inversely with the assumed average age.
15. Basaltic Volcanism Study Project, *Basaltic Volcanism on the Terrestrial Planets* (Pergamon, New York, 1981); P. Cattermole, *Planetary Volcanism* (Horwood, Chichester, U.K., 1989).
16. T. Simkin, *Annu. Rev. Earth Planet. Sci.* **21**, 427 (1993).
17. M. A. Bullock, D. H. Grinspoon, J. W. Head III, *Geophys. Res. Lett.* **19**, 2147 (1993); R. G. Strom, G. G. Schaber, D. D. Dawson, *J. Geophys. Res.* **99**, 10899 (1994).
18. J. A. Crisp, *J. Volcanol. Geotherm. Res.* **20**, 177 (1984); M. F. Coffin and O. Eldholm, *Rev. Geophys.* **32**, 1 (1994).
19. A. M. Rubin and D. D. Pollard, *Volcanism in Hawaii* [*U.S. Geol. Surv. Prof. Pap. 1350* (1987)], p. 1449; E. A. Parfitt, *J. Geophys. Res.* **96**, 10101 (1991); D. McKenzie, J. M. McKenzie, R. S. Saunders, *ibid.* **97**, 15977 (1992).
20. R. A. Schultz, *J. Geophys. Res.* **98**, 10883 (1993). Crustal pore pressure is negligible on Venus because of the absence of water, which may render the crust more resistant to dike propagation than on Earth. However, there is a disagreement of two or more orders of magnitude between experimentally determined and field estimates of fracture toughness (*19*).
21. B. Fegley Jr. and R. G. Prinn, *Nature* **337**, 55 (1989).
22. A χ^2 test yields a probability of 15% that the distribution of craters on coronae is identical to that for the entire planet; the probability that the two distributions are the same except for a scaling factor is 69%.
23. A. T. Basilevsky *et al.*, *J. Geophys. Res.* **91** (suppl., Proc. Lunar Planet. Sci. Conf. 16th), D399 (1986); E. R. Stofan and J. W. Head, *Icarus* **83**, 216 (1990); A. A. Pronin and E. R. Stofan, *ibid.* **87**, 452 (1990); S. W. Squyres *et al.*, *J. Geophys. Res.* **97**, 13611 (1992).
24. Areas covered by the different corona groups are 2.9, 3.5, 7.6, 6.7, and 5.6×10^6 km^2 for radial-volcanic, category 1, 2, 3, and 2r-3r coronae, respectively. The areas of the first two groups are too small to permit a reliable estimate of crater density, but the last three groups cover sufficiently large areas (*4*). On the basis of a χ^2 test, the probability that crater densities in Fig. 5 differ from random variations from an average is 68%.
25. K. M. Roberts and J. W. Head, *Geophys. Res. Lett.* **20**, 1111 (1993).
26. In the end-member equilibrium resurfacing model, the total number of impact craters on the surface, N^G, is described by

$$\frac{dN^G}{dt} = R_p S^G - u_r^G N^G$$

where R_p is the crater production rate per unit area, S^G is the surface area, and u_r^G is the fractional rate of removal of craters by global resurfacing. Similarly, the number of craters on volcanoes, N^V, is described by

$$\frac{dN^V}{dt} = R_p S^V - u_r^G N^V$$

where S^V is the area of volcanoes. Under equilibrium, $dN/dt = 0$. If S^V is constant in time, the crater density on volcanoes is equal to the global average density, R_p/u_r^G.
27. Errors in crater counts are taken to be equal to the square root of the number of craters.
28. On the basis of the crater database (*5, 8*), 18 large volcanoes have unmodified craters associated with them; 12 large volcanoes have associated embayed craters. These two populations of volcanoes do not overlap. There are four volcanoes which each have an associated deformed crater; two of these craters are also embayed. A total of 143 (82%) of the identified large volcanoes lack any associated impact craters.
29. From (*5*) and (*8*), 30 coronae have unmodified-craters, three coronae have embayed craters, and eight coronae have deformed craters. Artemis is the only corona displaying associated craters of different classes (one unmodified, two deformed, and two embayed); the three subsets of coronae do not otherwise overlap. A total of 319 coronae (89%) lack any associated impact craters.

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Discovery of Microwave Emission from Four Nearby Solar-Type G Stars

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Radio waves from the sun were detected 50 years ago, but the microwave detection of other single solar-type stars has remained a challenge. Here, the discovery of four solar-type radio stars is reported. These "solar twin" G stars are radio sources up to 3000 times stronger than the quiet sun. The microwaves most likely originate from a large number of relativistic electrons, possibly produced along with coronal heating, a process that is not understood. Two of the stars are younger than the sun and rotate more rapidly; the dynamo process in the stellar interior is therefore presumably more vigorous, resulting in enhanced coronal activity. One of the detections, however, is an old, metal-deficient G dwarf.

The magnetic dynamo in late-type stars results from an interaction between convection and differential rotation, so that coronal activity is expected to be strong in rapidly rotating stars. Consequently, young stars, often having short rotation periods, as well as interacting binaries of late spectral type should be prone to magnetic phenomena. In the radio domain, many red dwarf stars with emission lines in their optical spectra (dMe stars) are known not only as "radio flare stars" but as sources of "quiescent" microwave (~1 to 10 GHz) emission that is orders of magnitude more luminous than the sun; the latter emission is often ascribed to the gyrosynchrotron mechanism by nonthermal high-energy electrons. Only a few K stars, among them very young objects and rapid rotators, have been detected as strong radio sources (*1–4*). In a survey of solar-like stars, the dwarf χ^1 Ori was detected as a transient radio source (*5*), but this G star turned out to be a binary with an M-type companion (*6*). A very deep integration yielded a weak signal from the slightly evolved F5 IV-V star Procyon, compatible with thermal emission (*7*), while a small survey of FV stars revealed no further radio detections (*8*). A few G stars in RS CVn–type close binaries, forced to rotate rapidly, are known radio emitters (*9, 10*). Solar-like stars are thought to lose rapidly much of their initial angular momentum early in their lifetime. Therefore, nonthermal magnetic microwave activity of single stars is expected to decline rapidly with age and to become undetectable with present-day instruments at spectral types earlier than K. The sun, a middle-aged (~5×10^9 years) G2V single star, does not emit considerable continuous, nonthermal microwave radiation, and its free-free emission would be difficult to detect even at the distance of the nearest stars (~30 μJy at 1.3 pc).

The apparent dichotomy between strong stellar and weak solar microwave emission raises a number of questions: Is the prominent coronal activity of the coolest and the youngest stars intrinsically different from what we observe on the sun? Are coronae of the truly solar-type G dwarfs inherently much less prone to continuous or frequent acceleration of energetic particles? To address these questions and possibly link microwave activity on late-type stars to the solar analog (the "solar-stellar connection"), we conducted a deep microwave survey of 15 selected G stars with the Very Large Array (VLA) (*11*) at its sensitive X band (8.5 GHz) in

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A/B array configuration on 26 and 29 January 1993.

Our selection of targets may deserve a few comments. The quiescent radio luminosity (L_R) from an M dwarf is closely correlated with the stars' quiescent x-ray luminosity (L_x; $\log L_x - \log L_R \approx 15.5$ at 5 to 8.5 GHz) (*12*), a relation that is also suggested for K stars (*4*) as well as for active binaries and evolved stars (*9*, *10*, *13*). This relation motivated us to search the complete Roentgen Satellite (ROSAT) x-ray All-Sky Survey for Gliese (Gl) stars and Bright Stars in (*14*) of spectral class GV that could be detectable microwave sources if they followed the same luminosity relation. The x-ray luminosity was determined from the count rates with a standard conversion factor for a plasma temperature of about 10^7 K. Our targets presented below show steady x-ray emission about 100 to 800 times more luminous than the quiet sun ($L_x \approx 10^{27}$ erg s^{-1}). Several selected candidates were expected to be close to the microwave detection limit. Here, we report the first firm radio detections (signal-to-noise ratio $\gtrsim 6$) of four nearby solar-type G stars with high positional accuracy. Their microwave luminosities match our x-ray based predictions to within factors of $\sim 10^{0.05}$ to $10^{0.2}$ (Table 1).

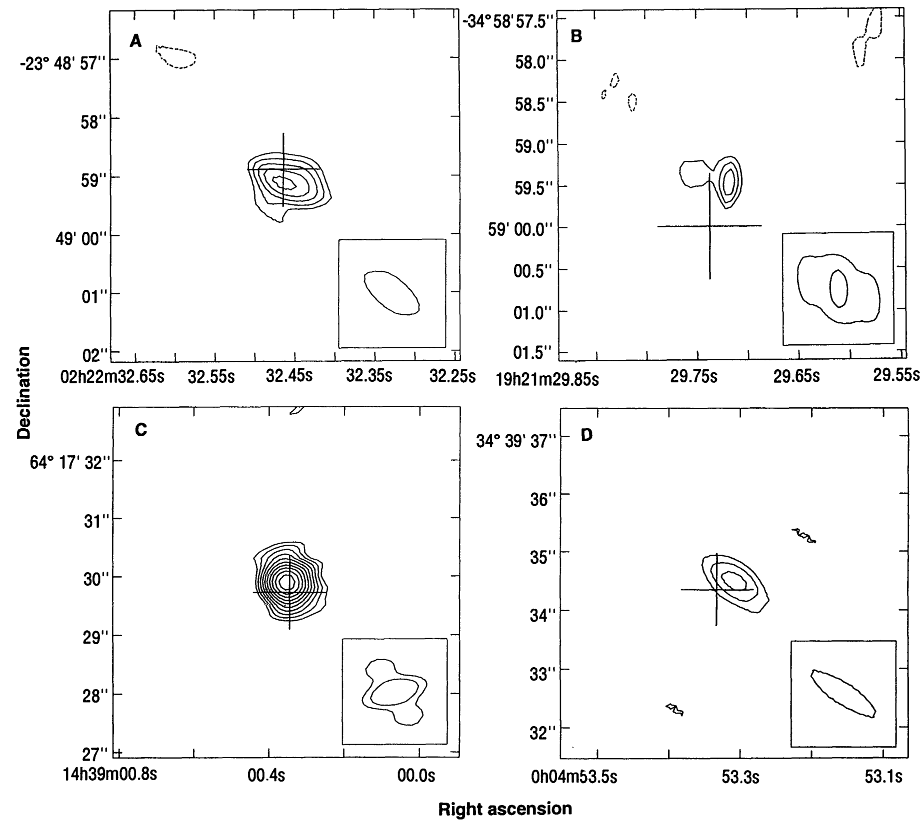

Fig. 1. Contour plots of the four microwave detections: (**A**) Gl 97, (**B**) Gl 755, (**C**) HD 129333, and (**D**) HD 225239. Contours are at (−3, 3, 4, 5 . . .)σ, where σ is the map noise root mean square. Each star was observed during ~45 min at 8.5 GHz, with application of standard flux and phase calibration procedures. The angular resolution in the maps is approximately 0.5 arc sec. All maps were analyzed by standard astronomical image processing system methods. The stellar images were cleaned and fitted with Gaussian models to derive the total fluxes in Table 1. The crosses define the optical positions at the epoch of our observations in the J2000 reference frame. The length of the error bars represents the statistical sum of the uncertainties in the optical and radio positions. The former include systematic and random errors in position and proper motion (adopted total of 0.6 arc sec), while the latter's errors comprise the maximum possible errors in our VLA phase calibrators (~0.15 arc sec) and the map pixel resolution (0.1 arc sec). The VLA observations of Gl 97 and Gl 755 were at relatively low elevations and are likely subject to some further deviations due to differential refraction. All detections are compatible with point sources. A few distortions of the cleaned stellar images are due to underlying, elongated noise features at the 2 to 3σ level. The extension at the 3σ level to the east of Gl 755 (Fig. 1B) is due to the extended VLA beam shape during A/B array reconfiguration. The insets show the beam at its 50% level (also 80% for Gl 755 and 30% for HD 129333).

Unambiguous identifications require high spatial resolution made possible with the interferometric technique. To illustrate the positional accuracy of our detections, we present in Fig. 1, A to D, contours of the radio sources along with the optical positions from (*15*); all errors are assigned to the optical positions for convenience. The observations yielded clear detections at the 6 to 13σ level within the error boxes from the optical positions.

The four stars have been frequent targets of optical surveys devoted to the study of solar twins. The bona fide solar-type star in our sample seems to be Gl 97 or κ Fornacis (Fig. 1A). Its spectral type, GlV, its equatorial *v*sin*i* of 4 km s^{-1}, (where *v* is the surface rotation velocity and *i* is the inclination of the axis to the line of sight), and its assumed age [$\sim 2 \times 10^9$ years, based on Li abundance and rotation velocity (*16*)] make it nearly solar-like (*17*). To the best of our knowledge, this star and Gl 755 (Fig. 1B) have not been identified as spectroscopic binaries in the published literature, although a conclusive proof of a star's singularity is exceedingly difficult, and all of our targets deserve to be included in future surveys addressing this question. At any rate, the x-ray luminosities of both stars exceed 10^{29} erg s^{-1}. At such large levels of x-ray luminosity, G-type stars are far more likely to be coronal x-ray emitters than M-type stars (as derived from x-ray popula-

Table 1. Values of x-ray luminosity (L_x), radio flux, radio luminosity (L_R), brightness temperature (T_B), and supplementary data for the detected stars; comparison with the sun.

Star	Spectral type	Distance (pc)	$\log L_x$ (erg s^{-1})	Radio flux (μJy ± 1σ)	$\log L_R$ (erg s^{-1} Hz^{-1})	T_B (10^7 K)	Age (10^9 years)	References
Gl 97	G1V	13	29.0	254 ± 35	13.71	1.1	~2	(*14*, *16*)
Gl 755	G5V	22	29.4	185 ± 31	14.03	2.4	—	(*29*)
HD 129333	dG0e	31	29.9	338 ± 25	14.59	8.6	~0.07	(*18*, *29*)
HD 225239	G2V	29	29.5	180 ± 30	14.26	4.0	~10	(*14*, *24*)
Quiet sun	G2V	5×10^{-6}	~27	$\sim 2 \times 10^{12}$	10.8	~0.001	~4.6	

tion studies in open clusters), and thus the x-rays should be attributed mostly to the G stars. Because the radio emission has the level expected from the radio/x-ray ratio of active stars (*13*), it likely originates also from the G stars.

The dG0e star EK Draconis, or HD 129333 (Fig. 1C), is a young solar analog just arriving on the main sequence [a probable kinematic member of the Pleiades moving group at an age of $\sim 70 \times 10^6$ years (*18*)] that rotates very rapidly (with a period of 2.7 days) (*19*) and shows high chromospheric and transition-region activity (*18*, *19*). A widely separated companion with a mass of >0.37 times the mass of the sun ($M_{\odot}$) has recently been suspected [orbit period ~12 years (*20*)], although little else is known about it. Such a system, because of its wide separation, can be treated as two noninteracting single stars. Although we cannot exclude microwave emission a priori from a cool companion, follow-up observations show evidence for the rotational modulation of microwave and x-ray emission precisely with the optical rotation period of the G star (*21*). Further, we notice that the measured L_R of $\approx 4 \times 10^{14}$ erg s^{-1} Hz^{-1} exceeds the low-level emission of most single M dwarfs [typically, $L_R \lesssim 1.5 \times 10^{14}$ erg s^{-1} Hz^{-1} (*12*, *22*), whereas for RST 137B, $L_R \approx 10^{15}$ erg s^{-1} Hz^{-1} (*23*)]. The identification of the radio source with the G star is also supported by the strong chromospheric activity and rapid rotation, which are clearly attributed to the G star.

The surprise detection in our sample is the star designated HD 225239 (Fig. 1D). Unlike HD 129333, this star is metal-deficient with a high space velocity, from the main sequence of the old-disk population and of the solar spectral type G2V, moving toward the sub-giant class (*24*). It is puzzling that a star much older than the sun supports microwave emission orders of magnitude brighter than even the strongest solar microwave flares ($L_R \approx 10^{12}$ erg s^{-1} Hz^{-1}). If HD 225239 were found to have a late-type companion, it would again appear unlikely that both x-ray and radio emission can be ascribed to this faint star. No old late-type M star has ever been found with x-ray luminosities nearly as high as HD 225239 (*25*). Radio sources of M stars are, not too surprisingly, also strongly biased toward the young disk population (*22*).

In Table 1 we estimate the brightness temperatures, T_B, of the radio emission, assuming a source size equal to the solar diameter. Strong radio emission from active stars generally cannot be reconciled with being thermal free-free emission from the coronal bulk plasma at temperatures of $\sim 0.1 \times 10^7$ to 2×10^7 K (*26*), because this classification would imply exceedingly large, optically thin sources (*5*). However, the plasma can become optically thick at the lowest coronal levels in the presence of strong magnetic fields (*5*), resulting in gyroresonance emission of the thermal plasma at low harmonics of the gyrofrequency. A large magnetic filling factor could account for the observed emission of Gl 97 and Gl 755. On the other hand, if the solar analogy has some merit and observational surface spot models can serve as a reference (*27*), radio emission should come from several more compact, localized active regions, increasing our estimates of T_B. However, 8.5-GHz radio emission of many other active stars is, as judged from microwave spectra, likely to be optically thin (*12*, *13*), indicating that the effective temperature, $T_{eff} \equiv T_B/\tau$, with $\tau < 1$. Thus, T_B may in fact constitute a rough lower limit to the effective temperature of the microwave-emitting electrons, suggesting emission by high-energy (very hot or nonthermal) electrons. Because microwave spectra are not yet available for our targets, the emission mechanism cannot be established. None of our detections are strongly circularly polarized, with upper limits between 24 and 57%. Also, we did not find obvious short-term flaring activity during the observing time of about 45 min per star. This result likely excludes coherent flares (although not long-duration incoherent flares) that are frequently observed on dMe flare stars and may suggest a more steady gyrosynchrotron emission mechanism, as in many active stellar coronae of M dwarfs and K stars. The close agreement between the predicted (from x-rays) and observed microwave luminosities further support the idea that efficient particle acceleration (as manifest in the microwaves) and coronal heating (responsible for strong x-rays) on these stars may be signatures of the same, probably flare-like, coronal energy release processes (*28*).

The detection of apparently steady, not strongly polarized and possibly nonthermal radio emission in the range of $13.7 \lesssim \log L_R \lesssim 14.6$ (two orders of magnitude stronger than the strongest solar flares) from four nearby solar-type, main-sequence G stars is a new discovery that contradicts the expectation that stars of optical spectral type G, and in particular solar-age or older main-sequence stars, cannot be detected as radio sources. It thus appears that there is—just as in the case of K- and M-type dwarf stars—a population of very active G stars that possibly maintain high-energy electrons in their coronae that can be detected through microwave emission. The dichotomy between active and inactive stars has therefore been extended into the range of the solar-type stars. In our sample, youth does not seem to be an unconditional ingredient, although further studies are needed to uncover the nature of the apparently old star HD 225239.

REFERENCES AND NOTES

1. J.-P. Caillault *et al.*, *Astron. J.* **95**, 887 (1988).
2. S. A. Drake *et al.*, *ibid.* **101**, 230 (1991).
3. J. Lim, G. J. Nelson, C. Castro, D. Kilkenny, F. van Wyk, *Astrophys. J.* **388**, L27 (1992).
4. M. Güdel, *Astron. Astrophys.* **264**, L31 (1992); *ibid.* **273**, 719 (1993).
5. D. E. Gary and J. L. Linsky, *Astrophys. J.* **250**, 284 (1981).
6. J. L. Linsky and D. E. Gary, *ibid.* **274**, 776 (1983).
7. S. A. Drake, T. Simon, A. Brown, *ibid.* **406**, 247 (1993).
8. J. A. Bookbinder and F. M. Walter, in *5th Cambridge Workshop on Cool Stars, Stellar Systems, and the Sun*, J. L. Linsky and R. E. Stencel, Eds. (Springer, Berlin, 1987), p. 260.
9. S. A. Drake, T. Simon, J. L. Linsky, *Astrophys. J. Suppl. Ser.* **71**, 905 (1989).
10. ——, *ibid.* **82**, 311 (1992).
11. The VLA is a facility of the National Radio Astronomy Observatory, which is operated by Associated Universities, Incorporated, under cooperative agreement with the U.S. National Science Foundation.
12. M. Güdel, J. H. M. M. Schmitt, J. A. Bookbinder, T. A. Fleming, *Astrophys. J.* **415**, 236 (1993).
13. M. Güdel and A. O. Benz, *ibid.* **405**, L63 (1993).
14. D. Hoffleit and C. Jascheck, *Bright Star Catalog* (Yale University Observatory, New Haven, CT, 1982).
15. C. Turon *et al.*, "Hipparcos Input Catalog," *Eur. Space Agency Spec. Pub.* SP-1136 (March 1992).
16. D. R. Soderblom, *Astrophys. J. Suppl. Ser.* **53**, 1 (1983).
17. B. M. Haisch and G. Basri, *Astrophys. J. Suppl. Ser.* **58**, 179 (1985).
18. D. R. Soderblom and S. D. Clements, *Astron. J.* **93**, 920 (1987).
19. J. D. Dorren and E. F. Guinan, *Astrophys. J.* **428**, 805 (1994); N. M. Elias II and J. D. Dorren, *Astron. J.* **100**, 818 (1990).
20. A. Duquennoy and M. Mayor, *Astron. Astrophys.* **248**, 485 (1991).
21. M. Güdel, J. H. M. M. Schmitt, A. O. Benz, N. M. Elias II, in preparation.
22. S. M. White, P. D. Jackson, M. R. Kundu, *Astrophys. J. Suppl. Ser.* **71**, 895 (1989).
23. J. Lim, *Astrophys. J.* **405**, L33 (1993).
24. C. P. Deliyannis, P. Demarque, S. D. Kawaler, *Astrophys. J. Suppl. Ser.* **73**, 21 (1990).
25. M. Barbera, G. Micela, S. Sciortino, F. R. Harnden Jr., R. Rosner, *Astrophys. J.* **414**, 846 (1993).
26. J. H. M. M. Schmitt *et al.*, *ibid.* **365**, 704 (1990).
27. M. Kürster, A. P. Hatzes, R. Pallavicini, S. Randich, in *7th Cambridge Workshop on Cool Stars, Stellar Systems, and the Sun*, M. S. Giampapa and J. A. Bookbinder, Eds. (Astronomical Society of the Pacific, San Francisco, CA, 1992), p. 249.
28. A. O. Benz and M. Güdel, *Astron. Astrophys.* **285**, 621 (1994).
29. W. Gliese, "Catalogue of Nearby Stars," Veroeff. Astron. Recheninstituts Heidelberg no. 22 (Braun, Karlsruhe, 1969).

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