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A VLA SURVEY OF NEARBY FLARE STARS

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ABSTRACT

The results of a VLA survey of nearby flare stars are presented, and combined with the results of other surveys to compare the incidence of radio detection of late-type dwarf stars with other stellar parameters. Our sample of flare stars included all known flare stars within 10 pc which had not been previously detected; approximately one-third of the sample stars were detected. The previously observed stars are among the most active flare stars, and, when they are included in the sample, about 40% of known nearby flare stars have been detected. Most of the detections in our survey were of flaring emission; we were unable to identify any good new candidates for quiescent emission from our sample, and argue that the more distant stars are likely to be too faint for study of their quiescent emission.

We compare radio detection with other stellar parameters in the larger sample. We find that there seems to be a deficiency of radio detections for M dwarf stars later than dM5.5, which agrees with the known falloff in X-ray luminosity of these late-type stars. The radio-detected stars generally have the largest X-ray fluxes of any stars of their spectral class or absolute luminosity, except for some stars of type dM4.5e. We do not find any strong correlation of radio detection with rotation period, but believe that this is due to a selection effect: most of the M dwarfs for which periods are known are very active flare stars and hence have been detected as radio sources. Support for a link between radio activity and rotation is found in the fact that most of the detected sources are stars which on kinematic grounds are believed to be young disk stars and hence, because of their youth, are still rapid rotators.

Subject headings: stars: evolution — stars: flare — stars: radio radiation — stars: rotation — stars: X-rays

I. INTRODUCTION

The radio emission of stars has been intensively studied with the Very Large Array[1] since its inception. Prior to the availability of the VLA's large collecting area and high spatial resolution, most stars were too faint to be reliably detected and distinguished from other, mostly extragalactic, radio sources. Major surveys have been carried out to find out what classes of stars are radio sources. Prominent among these are RS CVn and Algol-type binary systems (e.g., Morris and Mutel 1988), giant OB and M stellar wind sources (e.g., White and Becker 1985; Drake and Linsky 1986), magnetic Ap and Bp stars (Drake *et al.* 1987) and dMe flare stars. The latter were among the surprise detections in the first survey of stars carried out at the VLA (Gary and Linsky 1981), and since then many unexpected features of their radio emission have been discovered. In this paper, we report the results of the largest (to date) survey of flare stars, summarize the published observations of M dwarf stars, and look for correlations between stellar radio detections and other stellar parameters.

The survey consists of 20 cm and 6 cm observations of all known flare stars (most of which are M dwarfs, together with a few K dwarfs) within 10 pc visible from the VLA, as well as a few more distant candidates, but omitting those which had already been frequently observed at the commencement of the survey. The preliminary results of the first-epoch observations were presented earlier (Jackson, Kundu, and White 1987*b*); here we present the full sample, including second-epoch observations of many of the candidates. The survey was limited to flare stars, since they seemed the most likely candidates for detection based on the known radio sources. Subsequent surveys (Caillault, Drake, and Florkowski 1988; Willson, Lang, and Foster 1988; Kundu, White, and Agrawal 1988) have confirmed that flare stars as a subclass are more likely to be radio sources than the average M dwarf.

The radio emission of M dwarfs seems to be of two types: flaring emission and quiescent emission. We have argued elsewhere (Kundu *et al.* 1988), on the basis of long observations of four of these stars, that flaring is more common at 20 cm than at 6 cm wavelength, and thus one might expect more detections at 20 cm than at 6 cm. This is borne out by our results. However, quiescent emission seems to be more easily observed at 6 cm. One of the goals of this survey was to identify a number of good quiescent sources suitable for further study to identify the source of this emission.

Another aim of the survey was to have a large enough sample to find correlations between radio activity and other stellar parameters—in other words, to find a stellar property which acts as a "switch" for radio emission. Unfortunately, it will be seen that the relevant parameters (rotational period, age, chromospheric line widths, and so on) are only sporadically known, and we cannot reach any firm conclusions.

The results of the flare star survey are presented in § II. In § III we combine these with published data on other M dwarfs to compile a list of the observed M dwarfs. Using this

[1] The Very Large Array is a facility of the National Radio Astronomy Observatory, which is operated by Associated Universities, Inc., under cooperative agreement with the National Science Foundation.

list, we compare radio detections with several pertinent stellar parameters. A general discussion of the significance of these results is given in § IV.

II. OBSERVATIONS

The first epoch of observations was carried out over 30 hr on 1986 July 5, 10, and 11 with the VLA in A/B configuration. The candidates were chosen from Gurzadyan's (1980) list of flare stars (his Table 1.1). Classification of a particular star can vary with time; in particular, in recent years revived interest in flare stars and the solar-stellar connection seems to have led to more dedicated observations and the discovery that stars previously thought not to flare are in fact flare stars (e.g., Byrne 1981). Hence our set of flare stars is probably not complete, but presumably it includes the most active flare stars. Our selection from Gurzadyan's list is complete to 10 pc and includes a number of candidates out to 15 pc. We excluded the well-observed stars UV Cet, YY Gem, YZ CMi, AD Leo, Wolf 630, AT Mic, AU Mic, and EQ Peg, all of which we and others have detected in the course of other observations (see § III and Table 4 for references).

In the first epoch each star was observed for about 1 hr, with more time dedicated to 20 cm observations than to 6 cm observations in order to produce similar flux detection thresholds at both wavelengths. Deducting time for calibrator sources, this amounts to about 25 minutes of observation at 20 cm and 15 minutes at 6 cm. In some cases stars were observed twice on different days during the first epoch. The second-epoch observations were possible thanks to the VLA's generous policy of using small amounts of observing time available during periods set aside for maintenance and calibration. Observations were carried out in this mode on 1986 July 22 (Gl 406), July 29 (40 Eri C, Gl 229, Ross 986, WX UMa, SZ UMa, Ross 128), August 5 (Gl 22, Wolf 461, Gl 569, Gl 669, G208-44, DO Cep), September 21 (Wolf 47), October 24 (Gl 752, V1216 Sgr), November 23 (CQ And, Gl 908), December 4 (Wolf 461), 1987 January 20 (Wolf 1561, Gl 867, EV Lac), and February 14 (Gl 22). The observing durations for each star in the second epoch were shorter than in the first (20–30 minutes on source). Analysis of the data was carried out using the methods described in Jackson, Kundu, and White (1989).

The observed stars together with either their fluxes in the first-epoch whole-time maps, or else an upper limit based on all the data combined, are given in Table 1. Brightness temperatures are also given, based on the formula given in Kundu *et al.* (1987) which assumes unpolarized radiation, and a source size equal to that of the stellar disk (stellar radii will be given in Table 4). Several stars were not the prime candidates but happened to be in the VLA field of view. None of these "serendipitous" M dwarf stars (which are included in Table 4) were detected. Two systems (Gl 22, Gl 559) not present in the first-epoch observations reported by Jackson, Kundu, and White (1987*b*) were observed but not detected in the second epoch.

TABLE 1

SURVEY TARGETS

Gliese Number	Name	d (pc)	I_{20} (mJy)	V_{20} (mJy)	I_6 (mJy)	V_6 (mJy)	T_{20}	T_6
15AB.......	CQ And	3.6	<0.23	...	<0.22	...	$<7.7\times10^{8}$	$<6.9\times10^{7}$
22AB.......	...	10.4	<0.48	...	<0.39	...	2.0×10^{9}	1.5×10^{8}
*51	Wolf 47	9.3	5.17	<0.30	7.28	<0.37	1.0×10^{11}	1.2×10^{10}
54.1	...	7.0	<0.83	...	<0.39	...	$<2.7\times10^{9}$	$<1.2\times10^{8}$
83.1	...	4.7	<0.48	...	<0.26	...	$<1.6\times10^{9}$	$<8.0\times10^{7}$
166C	40 Eri C	4.8	<0.60	...	<0.27	...	$<1.7\times10^{9}$	$<7.0\times10^{7}$
229	HD 42581	5.7	<0.36	...	<0.29	...	$<2.3\times10^{8}$	$<1.7\times10^{7}$
*234AB.......	Ross 614	4.0	0.42	<0.21	0.55	<0.26	1.0×10^{9}	1.2×10^{8}
268	Ross 986	5.9	<0.30	...	<0.33	...	$<1.1\times10^{9}$	$<1.1\times10^{8}$
406	CN Leo	2.4	<0.58	...	<0.39	...	$<1.5\times10^{9}$	$<9.3\times10^{7}$
412AB.......	WX UMa	5.4	<0.25	...	<0.22	...	$<4.4\times10^{9}$	$<3.6\times10^{8}$
424	SZ UMa	8.5	<0.26	...	<0.24	...	$<5.8\times10^{8}$	$<5.0\times10^{7}$
447	Ross 128	3.3	<0.28	...	<0.21	...	$<6.4\times10^{8}$	$<4.5\times10^{7}$
*473AB.......	Wolf 424	4.3	0.40	<0.23	0.20	<0.27	1.7×10^{9}	8×10^{7}
*493.1	Wolf 461	10.1	0.72	<0.21	1.28	0.20	1.2×10^{10}	2.0×10^{9}
*494	DT Vir	12.1	0.44	<0.30	<0.34	<0.33	1.5×10^{9}	$<1.0\times10^{8}$
516AB.......	VW Com	16.0	<0.58	...	<0.32	...	$<7.5\times10^{9}$	$<3.8\times10^{8}$
517	EQ Her	18.8	<0.30	...	<0.25	...	$<1.2\times10^{9}$	$<9.4\times10^{7}$
540.2	Ross 845	13.8	<0.32	...	<0.35	...	$<7.7\times10^{9}$	$<7.9\times10^{8}$
569	...	10.4	<0.42	...	<0.39	...	$<1.5\times10^{9}$	$<1.3\times10^{8}$
*669AB.......	Ross 868/867	10.5	0.69(B)	<0.33	0.51(B)	<0.42	1.0×10^{10}	7.0×10^{8}
729	V1216 Sgr	2.9	<0.36	...	<0.30	...	$<1.5\times10^{9}$	$<1.2\times10^{8}$
752AB.......	B = VB10	5.8	<0.36	...	<0.29	...	$<3.2\times10^{10}$	$<2.4\times10^{9}$
....	G208-44, G208-45	4.7	<0.31	...	<0.31	...	$<2.7\times10^{9}$	$<2.5\times10^{8}$
791.2	...	9.4	<0.56	...	<0.35	...	$<7.7\times10^{9}$	$<4.5\times10^{8}$
852AB.......	Wolf 1561	9.7	<0.41	...	<0.29	...	$<7.3\times10^{9}$	$<4.5\times10^{8}$
*860AB.......	B = DO Cep	4.0	4.36	-1.57	12.83	-11.09	1.3×10^{10}	4×10^{9}
*867AB.......	...	8.3	0.27	-0.23	0.81	-0.24	1.4×10^{9}	4×10^{8}
*873	EV Lac	5.0	1.45	-1.20	<0.30	<0.27	2.6×10^{9}	$<5\times10^{7}$
908	...	5.7	<0.26	...	<0.20	...	$<3.7\times10^{8}$	$<2.7\times10^{7}$

TABLE 2

SECOND-EPOCH RESULTS FOR DETECTED STARS

GLIESE NUMBER	NAME	FIRST EPOCH I_{20}	V_{20}	I_6	V_6	SECOND EPOCH I_{20}	V_{20}	I_6	V_6
51	Wolf 47	5.17	< 0.30	7.28	< 0.37	< 0.48	...	< 0.27	...
493.1	Wolf 461	0.72	< 0.21	1.28	0.20	< 0.29	...	< 0.21	...
669B......	Ross 867	0.69	< 0.33	0.51	< 0.42	< 0.45	...	< 0.28	...
860B......	DO Cep	4.36	−1.57	12.83	−11.09	3.24	−2.60	< 0.39	...
867B......	...	0.27	−0.23	0.81	−0.24	8.31	−7.51	0.47	< 0.36
873	EV Lac	1.45	−1.20	< 0.30	< 0.27	<1.0	...	< 0.39	...

TABLE 3

POSITIONS OF DETECTED STARS (J2000)

Gliese Number	Name	Binary Separation (arcsec)	Position Type	R.A.	Decl.
51	Wolf 47	...	POSS	$01^h03^m18^s.61$	62°21′55″.5
			VLA	01 03 18.444	62 21 54.62
				±0.004	±0.03
234AB..........	Ross 614	1	POSS	06 29 22.8	−02 48 40.5
			VLA	06 29 22.817	−02 48 41.5
				±0.013	±0.2
473AB..........	Wolf 424	1	POSS	12 33 19.00	09 01 14.9
			VLA	12 33 19.0	09 01 12.5
				±0.10	±1.4
493.1	Wolf 461	...	POSS	13 00 34.26	05 41 06.8
			VLA	13 00 34.359	05 41 04.82
				±0.004	±0.06
494	DT Vir	...	POSS	13 00 47.13	12 22 33.7
			VLA	13 00 47.13	12 22 32.1
				±0.14	±1.5
					±1.5
669B	Ross 867	16	POSS	17 19 53.19	26 29 59.4
			VLA	17 19 53.19	26 29 58.1
				±0.03	±0.5
860	Kruger 60B, DO Cep	3	POSS	22 28 01.05	57 41 52.5
			VLA	22 28 01.197	57 41 49.18
				±0.003	±0.02
867A, 867B......	...	24	SAO (A)	22 38 45.20	−20 37 13.1
			VLA (B)	22 38 44.87	−20 36 50.85
				±0.01	±0.32
873	EV Lac	...	Gliese	22 46 50.79	44 19 56.81
			VLA	22 46 50.64	44 20 08.32
				±0.03	±0.38

As Table 1 indicates, of 29 systems, nine were detected. All nine were seen at 20 cm; seven of these were also seen at 6 cm. The results of the second-epoch observations are that none of the systems which were not detected initially were detected later; however, some systems seen in the first epoch were not seen in the second. We can only assume that this is due to the fact that the observation times were shorter in the second epoch: if, as argued above, detections are due to flares, then the chance of seeing a flare increases as the observation gets longer. The breakdown of the observations of the detected stars by epochs is given in Table 2, and their positions (J2000 coordinates corrected to epoch 1986.55) are compared with positions measured from the Palomar Sky Survey (POSS) in Table 3 (except for the stars Gl 867B and EV Lac, which were not measured: their positions are taken from the Gliese catalog (Gliese 1969) and are much less accurate than the POSS positions). The rms of the differences between the POSS positions and the VLA positions was 1″.2, which is about the uncertainty in the POSS positions (the VLA positions are mostly more accurate than this). A weak source at 6 cm near the expected position of Gl 83.1 was rejected as a detection due to the 10″ difference from the POSS position. A discussion of the individual detections follows.

1. *Gl 51 / Wolf 47.*—A relatively faint, late-type star (Gliese lists it as dM7e; Joy and Abt 1974 give dM5e). It was the strongest 20 cm source found in the survey, with a mean first-epoch flux of 5.2 mJy. This was unpolarized, but seems to have been highly variable: the time profile with 2 minute resolution is given in Figure 1 (these fluxes are obtained by cleaning individual maps and fitting a Gaussian to the source; a time profile with shorter time resolution is given in Jackson, Kundu, and White 1987*b*). It may also be showing narrow-

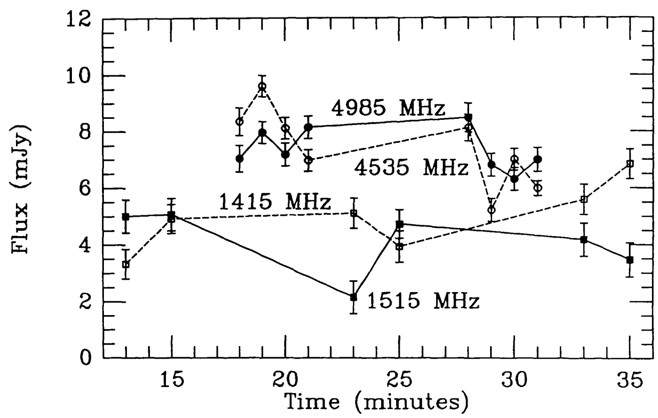

FIG. 1.—Time profile of radio emission from Wolf 47 at 6 cm (1 minute resolution) and 20 cm (2 minute resolution) wavelengths. The emission was unpolarized. The two frequencies observed in each band are plotted as follows: *open circle*, 4535 MHz; *filled circle*, 4985 MHz; *open square*, 1415 MHz: *filled square*, 1515 MHz. The error bars are $\pm 1\ \sigma$.

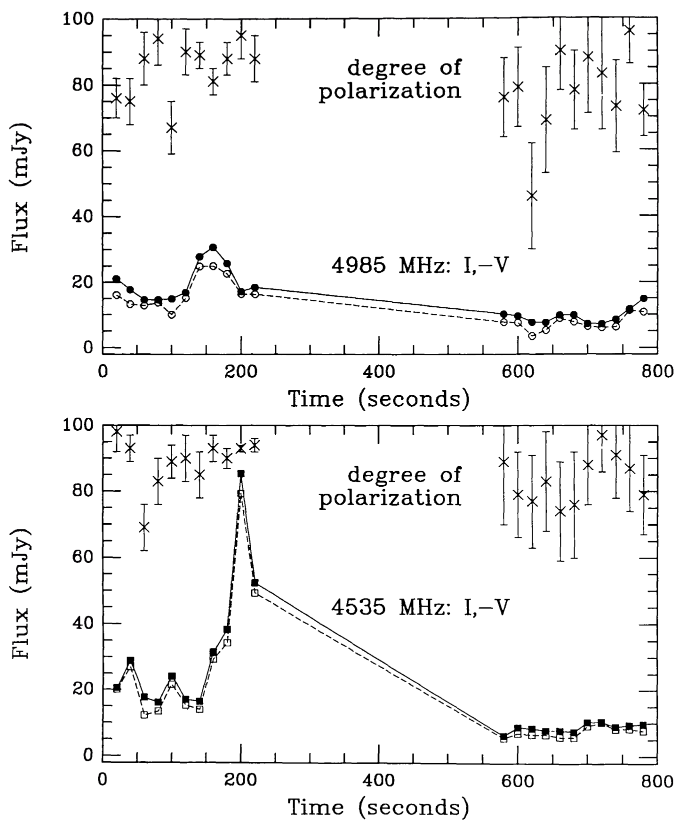

FIG. 2.—Time profile of a 6 cm flare from DO Cep at 20 s resolution. The upper panel shows *I* (*filled circles*) and $-V$ (circularly polarized flux; *open circles*) at 4985 MHz, while the crosses denote the degree of polarization (using the same numerical scale as the flux scale). The lower panel shows *I* (*filled squares*) and $-V$ (*open squares*) at 4535 MHz, together with the degree of polarization. One sigma error bars are plotted on all points.

bandedness, seen by comparing the 1415 and 1515 MHz curves. Apart from this fact, it seems to be similar to the highly variable but unpolarized 20 cm emission detected lasting for many hours on UV Cet by Bastian and Bookbinder (1987) and Kundu and Shevgaonkar (1988). The brightness temperature (10^{11} K) is somewhat high for gyrosynchrotron emission.

At 6 cm in the first epoch, Gl 51 was also strong and unpolarized, but showing no significant sign of narrow-bandedness (Fig. 1). The flux is clearly declining with time. The emission could again be similar to UV Cet's 6 cm quiescent emission, but at a much higher brightness temperature (10^{10} K).

However, Wolf 47 was undetected at the second epoch at either 20 cm or 6 cm (3 σ upper limits were 1.0 and 0.33 mJy, respectively).

2. *Gl 234 AB/Ross 614.*—A close pair with a combined spectral type dM4.5e (dM7e in Gliese). It shows relatively weak unpolarized emission at both 20 and 6 cm, for which time analysis was not feasible. Given the weak fluxes and the closeness of the binary, we cannot rule out the possibility that both stars are contributing. This system did not receive a second-epoch observation; however, Willson, Lang, and Foster (1988) failed to detect it at 6 cm with a flux limit of 0.18 mJy 2 weeks prior to our first-epoch observation.

3. *Wolf 424 AB/Gl 473.*—A binary pair of dM5.5e stars of similar magnitudes; thus it resembles UV Cet. One component shows relatively weak, unpolarized emission at both 20 and 6 cm (the 6 cm detection in particular is marginal). It was not detected by Fisher (1982). There was no second-epoch observation in this survey.

4. *Wolf 461/Gl 493.1.*—A single dM5.5e star. It shows weak unpolarized emission at 20 cm and stronger, possibly slightly polarized emission at 6 cm (however, the polarization detection is marginal). In the second epoch it was not detected.

5. *DT Vir/Gl 494.*—A single dM1.5e star. It was a 4.4 σ detection in the 20 cm map, with no significant polarization. It was not detected in the 6 cm map and did not receive a second-epoch observation.

6. *Ross 867/Gl 669B.*—A dM4.5e star in a wide binary with the dM4e star Ross 868/Gl 669A. It should be regarded as a marginal detection at both 20 and 6 cm. It was not detected in the second-epoch observations.

7. *DO Cep/Gl 860B.*—The partner of Kruger 60A in a binary with about 2″ separation. Only the B component was seen. It was strong and highly polarized at both 20 and 6 cm. It was observed twice during the first epoch. On the first day at 6 cm, it displayed the strongest 6 cm flare yet seen from this class of stars (shown at 20 s time resolution in Fig. 2, based on fits to maps of each 20 s period). It was approximately 95% polarized, and was clearly different at two frequencies 450 MHz apart (while showing some similarities). At 20 cm on the first day it was apparently much less variable, and less polarized. On the second day, DO Cep was weaker, less variable, but still strongly polarized at 6 cm, and weak and unpolarized at 20 cm. In the second-epoch observations DO Cep was not detected at 6 cm. At 20 cm DO Cep was strongly polarized with no narrow-band effects. At 1415 MHz, $I = 3.0$ mJy (rms 0.6 mJy) and $V = -2.6$ mJy (rms 0.17 mJy), while at 1515 MHz $I = 3.0$ mJy (rms 0.4 mJy) and $V = -2.7$ mJy (rms 0.30). Further time analysis was not attempted. It is of interest that the degree of polarization in this observation, $\sim 90\%$, is similar to that of the 6 cm flare in Figure 2. We

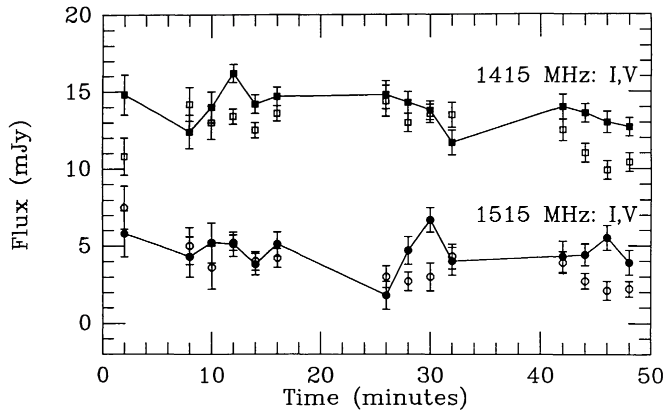

FIG. 3.—Narrow-band flare from GL 867B at 2 minute resolution. At 1415 MHz I and V are represented by filled and open squares, respectively; at 1515 MHz I and V are represented by filled and open circles. The error bars are $\pm 1\ \sigma$.

note here that in the course of other programs we observed DO Cep for longer periods in 1987 June, failing to detect it at 20, 6, or 2 cm, and in 1987 November, failing to detect it at 20 cm or 6 cm. This seems to indicate that the extreme activity seen in the first epoch is a rare occurrence.

8. *Gl 867B.*—A dM3e star in a visual binary (separation ~ 22″) recently shown to have BY Dra variability (Doyle, Byrne, and Butler 1986). In the first-epoch observation it was a marginal detection at 20 cm but relatively strong at 6 cm (polarization detection marginal). However, in the second-epoch observation it displayed a strongly polarized, narrow-banded flare at 20 cm (Fig. 3), while being weakly present at 6 cm.

9. *EV Lac/Gl 873.*—The 20 cm field containing EV Lac is one of the most difficult to clean of all flare star fields known to us, because of the presence of numerous point sources and a large biconical linearly polarized nebula close to the star. However, EV Lac was clearly detected at 20 cm in the first epoch as a negatively polarized source, apparently because of flaring. It was not detected at 6 cm in the first epoch, and not detected at 20 cm or 6 cm in the second epoch (albeit with a high detection threshold as a result of the confused field). Willson, Lang, and Foster (1988) did not detect it at 6 cm in 1986 June, but Caillault, Drake, and Florkowski (1988) did detect it as an 0.96 mJy source at 6 cm (they did not mention polarization) in 1985 September, while failing to detect it at 6 cm in 1986 February. Hence this source is quite variable.

Five of the detections in this survey were of one component of a binary system, with the other component not detected. In the case of both Gl 234AB and Wolf 424AB, we believe that the earlier type (dM4.5e and dM5.5e, respectively) star was detected, while the very late type (later than dM6) component was apparently undetected (however, in the case of Wolf 424AB our spatial resolution is insufficient to be sure). In the other three cases the brighter component was undetected, while the later type component was detected: this occurred in Gl 669AB (dM4e + dM4.5e), Gl 860AB (dM3.5 + dM4.5e), and Gl 867AB (dM2e + dM3e). This behavior among the binary systems is in agreement with a result we find in the larger sample discussed in the next section: that radio detections are more common around dM4e–dM5.5e than at either earlier or later types.

III. VLA OBSERVATIONS OF LATE-TYPE DWARF STARS

In Table 4 we collect the properties of some 83 dM and late-type dK stars observed by the VLA, using all the published data available. The principal sources are this paper, Willson, Lang, and Foster (1988), Caillault, Drake, and Florkowski (1988), and Kundu, White, and Agrawal (1988). We restrict our survey to VLA observations, since they provide a consistent set, and since most other observations were made with single-dish telescopes which have poorer discrimination against interference and confusion than a synthesis instrument such as the VLA. There are a small number of Westerbork observations of the better known flare stars (e.g., van den Oord 1987). Wendker (1987) presents a catalog of essentially all radio observations of stars prior to 1985. Interferometers operating at low frequencies (< 200 MHz; Ooty synthesis radio telescope, A. P. Rao, T. Velusamy, and V. Venugopal, private communication; Clark Lake synthesis telescope, Jackson, Kundu, and Kassim 1989) have failed to detect flare stars in many hours of observations; however, the detection level of these observations is high (at least 100 mJy). At decimeter frequencies, the Molonglo synthesis telescope has made numerous detections of stars at 843 MHz, including AT Mic (e.g., Vaughan and Large 1986), and the VLA has now detected YZ CMi at 327 MHz (Kundu and Shevgaonkar 1988).

The list in Table 4 is complete for flare stars within about 10 pc (visible from the VLA), but for no other category of star, and therefore the statistics one derives from this survey are strongly biased by the predominance of flare stars. We note also four other stars in the Gliese catalog which were present in the observed fields but were not detected: the K dwarf Om Eri (Gl 166A), the A star Gl 166B, the white dwarf Gl 169.1A, and the G5 star MU Her (Gl 695). When the detections in Table 4 are broken down into classes, we find the following: 24 out of 57 (42%) flare stars were detected; 25 out of 60 (42%) dMe/dKe stars were detected; one out of 22 (5%) dM/dK stars were detected; and 11 out of 17 (65%) BY Dra–type stars were detected. Barnard's star (Gl 669), whose detection at 6 cm by Bookbinder was reported by Winglee, Dulk, and Bastian (1986), although they themselves did not detect it, is the only non–emission-line star among the radio detections. It seems clear from the above statistics, despite the acknowledged bias, that generally dM stars are not radio sources, and that the radio flares which form the basis of most detections are linked to the forms of activity indicated by optical flaring or the presence of chromospheric emission lines in the optical spectra. The level of chromospheric activity necessary to produce chromospheric lines in absorption (Cram and Mullan 1979; Cram and Giampapa 1987) is apparently inadequate to produce radio flaring.

Despite the disappointing results of our second-epoch survey, we believe that many of the flare stars presently undetected in short survey observations would be detected as radio sources if observed over a long period of time. The observations of DO Cep at several epochs discussed here show that radio behavior is highly variable on the time scale of months or years. Thus we believe that most of the nearby flare stars

TABLE 4

DWARF STAR OBSERVATIONS BY THE VLA

Gliese Number (1)	Name (2)	Type (3)	M (4)	d (5)	$R_*/R_\odot$ (6)	$\log_{10} L_x$ (7)	Hα (8)	P (9)	Binary Information (10)	Comments (11)	References (12)
15A	BD +43°44	dM2.5	10.32	3.6	0.50	27.2	−0.28	...	40″	F, $B<1500$	1, 2
15B	CQ And	dM4.5e	13.29	3.6	0.19	...	0.0	...	...	F	1, 2
22A	BD +66°34	dM2.5	10.42	10.4	0.49	...	−0.14	...	3″	F	1
22B	...	dM4.5	12.3	10.4	0.31	...	...	...	...		1
29.1	FF And	dM1e	8.7	21.3	0.75	29.5	2.27	2.17	SB	BY Dra	2, 3
49	Wolf 46	dM2	9.72	9.3	0.62	...	−0.27	...	SB?		1
*51	Wolf 47	dM5e	13.81	9.3	0.21	...	...	...	...	F	1
54.1	L725-32	dM5.5e	12.4	7.0	0.37	...	...	...	...	F	1
*65A	L726-8A	dM5.5e	15.27	2.7	0.16	27.5	...	...	2″	F	4
*65B	UV Cet	dM6e	15.8	2.7	0.15	27.5	...	...	...	F	4
83.1	TZ Ari	dM8e	13.9	4.7	0.25	27.6	...	...	...	F	1
103	CC Eri	dK7e	8.4	11.4	0.81	29.4	...	1.56	EB, SB	F, BY Dra	3
166C	40 Eri C	dM4e	12.73	4.8	0.28	28.3	...	...	83″, 6″9	F	1, 2
169.1A	...	dM4	12.51	5.2	0.29	...	...	...	7″		5
182	V1005 Ori	dM0.5e	8.8	14.7	0.73	29.3	...	1.96	...	BY Dra	2, 6
*206	Ross 42	dM4e	10.73	14.2	0.46	29.1	3.17	...	SB	F	7
207.1	V371 Ori	dM2.5e	10.8	15.2	0.45	...	4.42	...	...	F	2
213	Ross 47	dM4.5	12.73	6.0	0.32	27.2	−0.21	...	...		7
229	HD 42581	dM2.5	9.33	5.7	0.69	26.9	−1.1	...	...	F, $B=2500$, $f=0.2$	1, 2, 7
*234A	Ross 614A	dM4.5e	13.08	4.0	0.25	26.5	3.56	...	1″	F	1, 2
234B	Ross 614B	dM7?	16.4	4.0	0.11	...	...	...	...	F	1, 2
268	Ross 986	dM5e	12.62	5.9	0.30	27.5	1.86	...	SB	F	1
*278C	YY Gem	dM1e	8.26	14.5	0.83	29.5	4.0	0.81	EB, SB	F, BY Dra	4
*285	YZ CMi	dM4.5e	12.29	6.0	0.30	28.5	7.48	2.78	...	F, BY Dra	4
*388	AD Leo	dM3.5e	10.98	4.9	0.50	29.0	3.43	2.70	...	F, $B=4300$, $f=0.7$	4
406	Wolf 359, CN Leo	dM6.5e	16.68	2.4	0.15	27.0	10.46	...	...	F	1, 2, 8, 9
411	HD 54735	dM2	10.49	2.5	0.47	...	−0.28	...	...		5
412A	...	dM2	10.12	5.4	0.50	...	−0.33	...	28″		1
412B	WX UMa	dM5.5e	15.88	5.4	0.13	27.5	...	...	...	F	1
424	SZ UMa	dM1.5	9.70	8.5	0.55	...	−0.40	...	...	F	1, 2
...	BD +48°1958A	dM0e	8.9	17	0.45	...	...	1.30	...	BY Dra	3
447	Ross 128	dM4.5	13.50	3.3	0.21	26.6	0.01	...	...	F	1, 2, 7
461	...	dM2	9.1	16.7	0.68	28.2	...	...	...		7
*473A	Wolf 424A	dM5.5e	14.98	4.3	0.20	...	...	...	1″	F	1, 8
473B	Wolf 424B	dM7?	15.2	4.3	0.20	...	...	...	...	F	1, 8
*493.1	Wolf 461, FN Vir	dM5e	13.3	10.1	0.24	27.9	...	...	SB	F	1
*494	DT Vir, Ross 458	dM1.5e	9.1	12.1	0.63	29.4	2.12	1.54	...	F, BY Dra	1, 2
514.1	Ross 476	dM6	13.1	17.5	0.25	28.0	...	...	...		7
516A	VW Com	dM3.5e	11.1	16.0	0.42	27.9	0.01	...	3″	F	1
516B	...	dM4e	11.4	16.0	0.39	...	0.01	...	...	F	1
517	EQ Vir	dK5	8.0	18.8	0.89	29.4	0.01?	3.96	...	F, BY Dra, $B=2500$	1, 2, 10
540.2	Ross 845	dM5e	12.8	13.8	0.27	...	...	...	...	F	1
569	...	dM2e	10.1	10.4	0.53	28.7	3.58	...	...	F	1, 8
616.2	CR Dra	dM1.5e	8.4	16.3	0.72	29.1	1.81	...	...	F	7
630.1A	CM Dra	dM4e	12.0	14.9	0.33	28.5	...	1.27	EB; 26″	BY Dra	3
630.1B	...	dM7?	14.1	14.9	0.20	...	...	...	...		3
643	Wolf 629	dM4	12.73	6.2	0.20	< 27.0	−0.26	...	SB; 72″ with Gl 644		4
*644A	Wolf 630A	dM4.5e	10.79	6.2	0.50	29.1	1.73	1.71	0″2	F	4
644B	Wolf 630B	dM4.5	10.8	6.2	0.50	...	...	...	...	F	4
644C	VB 8	dM7?	17.69	6.2	0.08	26.7	...	...	...		4
669A	Ross 868	dM4e	11.25	10.5	0.40	...	1.63	...	16″	F	1
*669B	Ross 867	dM4.5e	12.81	10.5	0.27	28.6	5.67	...	...	F	1
687	...	dM4	10.79	4.7	0.47	26.9	...	...	SB		5
695B	...	dM3.5	10.80	8.1	0.45	27.6	...	...	1″4		7
695C	...	dM4	11.26	8.1	0.40	...	...	...	...		7
*699	Barnard's star	dM4.5	13.25	1.81	0.20	26.1	...	...	...		5
*719	BY Dra	dM0e	7.6	15.6	0.99	29.5	...	3.83	SB	F, BY Dra	3, 7, 11
725A	HD 173739	dM4	11.15	3.5	0.41	...	−0.22	...	16″		2
725B	HD 173740	dM4.5	11.94	3.5	0.34	26.8	−0.21	...	...		2
729	V1216 Sgr, Ross 154	dM4.5e	13.3	2.9	0.14	27.7	...	...	...	F	1
*735	V1285 Aql	dM3e	9.9	10.9	0.56	28.9	1.69	2.4	SB	F	2, 7

TABLE 4—*Continued*

Gliese Number (1)	Name (2)	Type (3)	M (4)	d (5)	$R_*/R_\odot$ (6)	$\log_{10} L_x$ (7)	Hα (8)	P (9)	Binary Information (10)	Comments (11)	References (12)
752A	Wolf 1055, Ross 652	dM3	10.31	5.8	0.58	...	−0.35	...	74″		1, 2
752B	VB 10	dM5e	18.57	5.8	0.059	27.0	...	...	...	F	1, 2
...	G208-44AB	dM6e	15.1	4.7	0.15	...	...	...	1″; 8″	F	1
...	G208-45	dM6e	15.7	4.7	0.13	...	...	...	...	F	1
791.2	...	dM6e	13.2	9.4	0.25	28.1	...	...	...	F	1
*799A	HD 196982, AT MicA	dM4.5e	11.09	8.8	0.41	29.3	...	...	3″	F, BY Dra	6, 12
*799B	AT MicB	dM4.5e	11.2	8.8	0.40	...	...	...	...	F, BY Dra	6, 12
*803	HD 197481, AU Mic	dM0e	8.87	8.8	0.56	29.8	8.70	4.85	...	F, BY Dra, $B = 4000$	6, 12, 13
852A	Wolf 1561A	dM4.5e	13.6	9.7	0.22	...	...	...	8″	F	1
852B	Wolf 1561B	dM5e	14.6	9.7	0.17	...	...	...	...	F	1
860A	Krüger 60A	dM3.5	11.87	4.0	0.35	...	0.01	...	3″	F	1
*860B	DO Cep	dM4.5e	13.3	4.0	0.22	27.4	...	...	...	F	1
866	L789-6	dM5.5e	14.60	3.3	0.22	27.0	...	...	...	F	7
867A	HD 214479	dM2e	9.3	8.3	0.69	...	...	4.1	SB; 24″	BY Dra	1
*867B	...	dM3e	11.6	8.3	0.35	29.5	...	1.95	...	F, BY Dra	1
*873	EV Lac	dM4.5e	11.65	5.0	0.35	...	3.36	4.37	5″?	F, BY Dra, $B = 5200$	1, 2, 3, 5
*890	...	dM2.5e	9.1	20.0	0.68	...	...	0.43	...		6
*...	HD 218738	dK2	6.5	19.4	0.8	...	...	3.03	...	BY Dra	3
*896A	...	dM4e	11.33	6.4	0.39	28.8	4.26	...	5″	F	4
*896B	EQ Peg	dM5e	13.4	6.4	0.23	...	5.11	...	...	F	4
905	Ross 248, HH And	dM5.5e	14.80	3.1	0.19	26.3	−0.24	...	...		7
908	...	dM2.5e	10.19	5.7	0.46	...	−0.40	...	...	F	1

NOTE.—An asterisk preceding the Gliese number indicates that the star has been detected as a radio source.

Col. (1).—Gliese catalog number of the star (Gliese 1969).

Col. (2).—Common names.

Col. (3).—Spectral type, taken from Joy and Abt 1974 where possible, otherwise from the Gliese catalog.

Col. (4).—Absolute magnitude, using the same sources as col. (3).

Col. (5).—Distance in parsecs, using the parallaxes in the Gliese catalog.

Col. (6).—Stellar radius in units of 1 solar radius; the source is Lacy 1977 where possible; otherwise his mean relation $\log(R_*/R_\odot) = 0.816 - 0.108 M_v$ (valid for $M_v > 9$) has been used.

Col. (7).—Logarithm of the quiescent X-ray flux, using either *Einstein* observations (from the lists in Agrawal, Rao, and Sreekantan 1986 and Johnson 1986) or *EXOSAT* observations (Schmitt and Rosso 1988), in units of ergs s^{-1}.

Col. (8).—Hα equivalent width, from Stauffer and Hartmann 1986 or Worden, Schneeberger, and Giampapa 1981. Note that the Hα width tends to be variable, particularly when the line is in emission.

Col. (9).—Period in days, where known.

Col. (10).—Binary information for eclipsing binaries (EB) and spectroscopic binaries (SB); where the star is a visual binary, the approximate binary separation is given.

Col. (11).—F and BY Dra indicate that the star is a known flare star or a BY Dra variable; B is the average magnetic field strength in gauss; and f is the filling factor as a fraction of the surface area, taken from Saar, Linsky, and Giampapa 1987.

Col. (12).—References discussing VLA observations of each star.

REFERENCES.—(1) Jackson, Kundu, and White 1987*b*; this paper. (2) Willson, Lang, and Foster 1988. (3) Caillault, Drake, and Florkowski 1988. (4) (Frequently observed) Gary and Linsky 1981; Fisher 1982; Linsky and Gary 1983; Gary, Linsky, and Dulk 1982; Gary 1985, 1986; Foing *et al.* 1986; Bastian 1987; Bastian and Bookbinder 1987; Gary, Byrne, and Butler 1987; Jackson, Kundu, and White 1987*a*; Kundu and Shevgaonkar 1985; Kundu and Shevgaonkar 1988; Kundu *et al.* 1988; Lang and Willson 1986, 1988; White, Kundu, and Jackson 1986; Rodonò 1987; Kundu, Jackson, and White 1988; Güdel and Benz 1989; Large *et al.* 1989; Jackson, Kundu, and White 1989. (5) Winglee, Dulk, and Bastian 1986. (6) Slee *et al.* 1988. (7) White, Kundu, and Agrawal 1988. (8) Fisher 1982. (9) O'Dea and McKinnon 1987. (10) Pallavicini, Willson, and Lang 1985. (11) Florkowski *et al.* 1985. (12) Kundu *et al.* 1987. (13) Cox and Gibson 1985.

are likely to be detected as radio sources, but that their flux level averaged over long periods of time is insignificant. Thus, despite the ubiquity of M dwarf stars in the Galaxy, they are unlikely to constitute a significant fraction of all known radio sources.

All of the nearby flare stars identified from optical observations as among the most active have been found to be radio sources. Thus it is clear that whatever activity produces the vigorous optical and X-ray flaring also produces radio flaring (even though, as we have discussed elsewhere, flares in the different wavelength domains show little correlation, and the radio flares are quite unlike anything seen on the Sun; Kundu *et al.* 1988). It is therefore important to try to identify stellar parameters which can act as indicators of radio emission and might give some clue to the physical nature of the underlying mechanism (widely believed to be magnetic activity due to the rapid rotation of young stars with deep convection zones). Table 4 therefore includes the quiescent X-ray fluxes, periods, Hα equivalent widths, and magnetic fields of those stars for which we can find measurements in the literature. We have also used the space motions listed in the Gliese (1969) catalog. Correlations of various of these parameters with radio detection are given as scatter plots in Figures 4–8 and are discussed below. We note that nowhere do we plot radio fluxes against other parameters This is because we believe that the flaring flux of these stars has little relevance to the energetics of the stars, since the emission mechanism must be coherent (and hence the flux magnitude need bear little relation to the underlying energy release). Only in a very few cases can we confidently identify the quiescent radio flux of a star. Most observations have been of short duration, and it is exceedingly difficult to discriminate between flaring and quiescent emission for such observations. Those stars which have been observed for long periods have shown a range of behaviors, further complicating this discrimination (an example is the observation of unpolarized flaring on Wolf 47 [this paper] and on Gl 735 [Kundu, White, and Agrawal 1988]). Since short observations are also inadequate to discuss the long-term average flaring flux of these stars, we prefer only to use radio detection as the measure of radio activity. Similarly, it is clear that radio properties are more rapidly variable than other quiescent stellar properties such as quiescent X-ray flux, and thus simultaneous observations at all wavelength ranges are needed to make any quantitative comparison.

In Figure 4 we plot the stars in Table 4 against absolute luminosity and spectral type. (To avoid clustering of points we have introduced small shifts where necessary. In this figure negative values of spectral type refer, somewhat arbitrarily, to dK stars, while positive values correspond to the spectral type of a dM star, e.g., a value of 3.5 implies a dM3.5 star.) The stars all naturally fall close to the main-sequence curve on this diagram. Circles indicate dMe stars, and triangles are dM stars; open symbols indicate no detection, and closed symbols indicate detection. As is well known (e.g., Stauffer and Hartmann 1986), flare stars tend to be overluminous compared with dM stars of the same color, and this effect is evident for the radio detections earlier than dM4. This figure shows an apparent deficiency of detections of stars of type later than dM5.5. This would agree with a similar result for the X-ray behavior of these stars, which is known to decrease at spectral types later than dM6 (Bookbinder 1985). When we count the various spectral types separately, we find the following: one out of three (33%) dK stars were detected; four out of nine (45%) dM0–dM1.5 stars were detected; four out of 19 (24%) dM2–dM3.5 stars were detected; 16 out of 41 (39%) dM4–dM5.5 stars were detected; and one out of 11 (9%) dM6 and later stars were detected. We should note again that, particularly at types above dM2, this survey is strongly biased

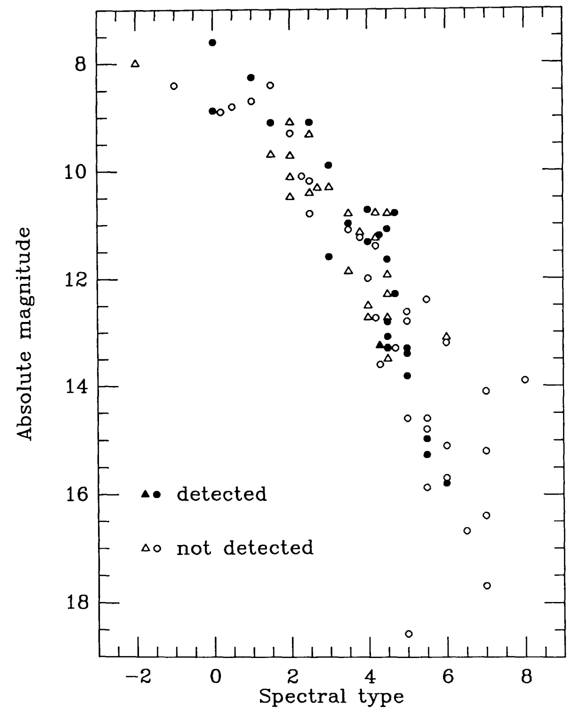

FIG. 4.—Plot of radio detections on the H-R diagram (here absolute magnitude vs. spectral type). Circles are dMe/dKe stars, and triangles are dM/dK stars; closed symbols indicate radio sources, whereas open symbols represent stars not yet detected as radio sources. The axis for stellar type shows dK stars as having negative values (the more negative, the earlier in type), with positive values denoting the type of a dM star (e.g., a value of 4.5 corresponds to a dM4.5 star). Small shifts have been introduced where necessary to avoid clustering.

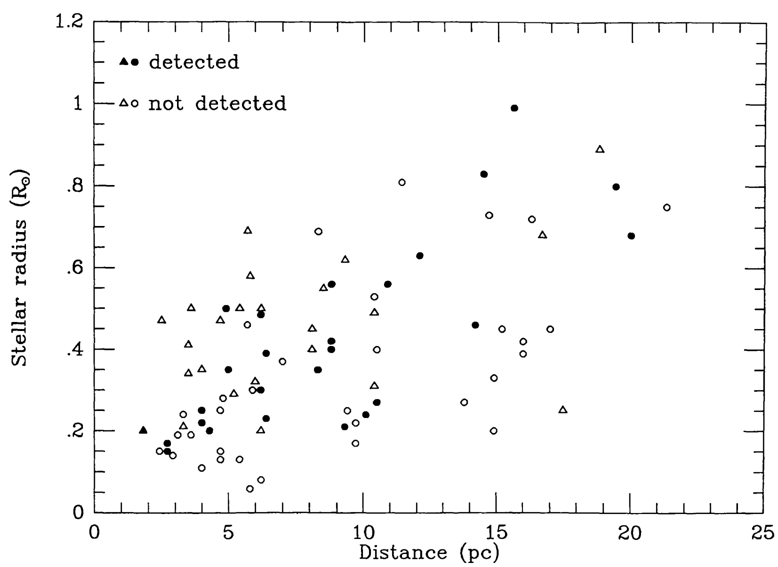

FIG. 5.—Scatter plot of detections vs. distance and stellar radius, with the same symbols as in Fig. 4.

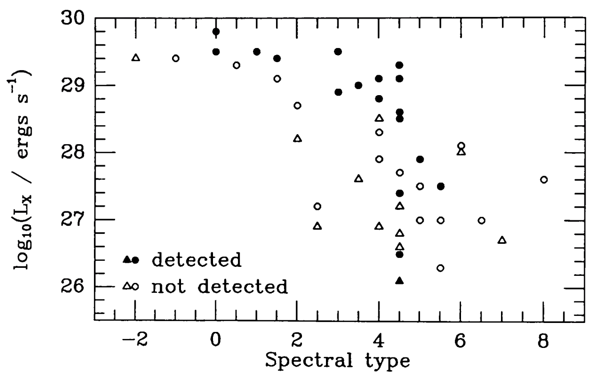

FIG. 6.—Scatter plot of X-ray fluxes vs. spectral type. The symbols are as in Fig. 4.

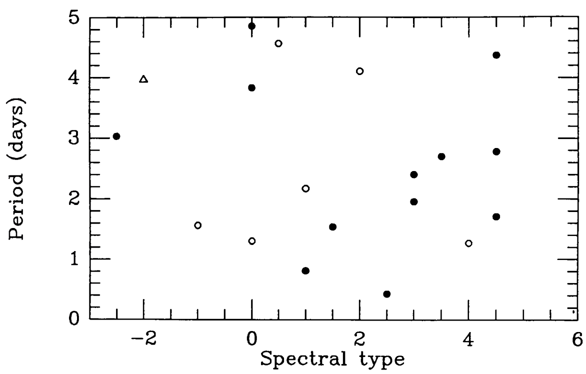

FIG. 7.—Scatter plot of radio detections vs. spectral type and rotational period.

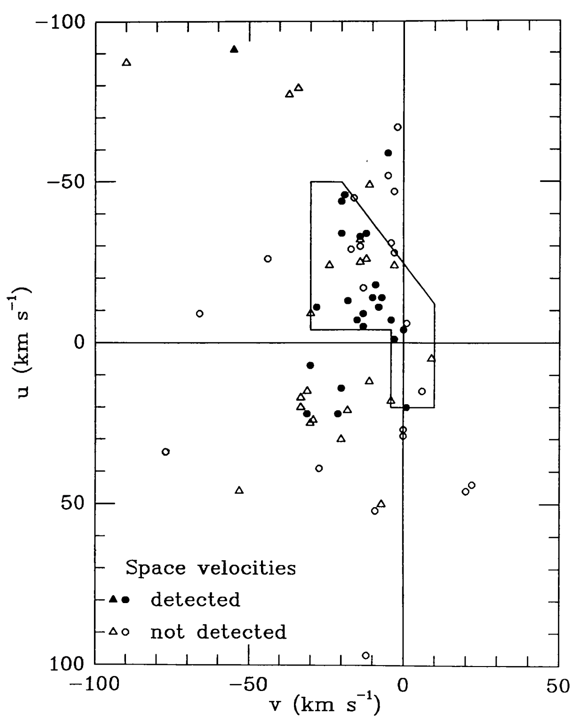

FIG. 8.—Scatter plot of radio detections on a space-velocity (relative to solar) diagram. The outlined region is the location of the "young disk" population identified by Eggen (1977).

by the presence of flare stars. Thus we do not believe that the apparent deficiency of detections of types dM2–dM3.5 is significant in this sample. However, the deficiency of late-type stars appears to be significant, since the known members of this class of faint stars should be biased in favor of activity.

Figure 5 is a scatter plot of distance versus radius. There is no obvious distance effect present in the detection rate out to 10 pc, to which distance the survey is complete, and in fact the detection rate beyond 10 pc is about the same as that within 10 pc (however, the proportion of dMe stars is greater in the sample beyond 10 pc, and the more distant stars were selected for activity). We argue that radio detection of stars in the volume of this survey is not distance-limited. We believe that this is because most of the detections are of flaring, which shows a large variability of flux, more important than distance in the incidence of detection. We assume that the detection rate of the quiescent component alone probably would show distance-limiting effects if it were possible to isolate it in the data. This follows, since it would be difficult to recognize the quiescent emission of UV Cet if it were at a distance of 10 pc.

Figure 6 plots the absolute quiescent X-ray flux against spectral type for those stars observed in X-rays (note that a very large fraction of the M dwarf stars for which X-ray observations exist have been observed with the VLA). The figure shows a concentration of radio detections for stars with the largest X-ray fluxes at a given spectral type. These stars also tend to be among the brighter (i.e., earlier type) stars in this figure, which may reflect a bias in the X-ray observations. Interestingly, the only two stars with X-ray fluxes in excess of 10^{29} ergs s^{-1} which are not radio sources are dK stars (CC Eri and EQ Vir). With a few exceptions, Figure 7 suggests that for a given absolute magnitude (or spectral type) the radio sources are those stars with the largest X-ray fluxes, again reflecting the general correlation between activity at all wavelengths for an active star. There seem to be exceptions to this rule around spectral type dM4.5, which show radio detection at low X-ray fluxes. However, the number of examples is small.

The prime candidate as an indicator of extreme magnetic activity is thought to be the rotation rate of the stars (or, more specifically, the Rossby number which appears in dynamo theory). We can find periods in the literature for 17 of the stars in this survey, and these are plotted against spectral type in Figure 7. This plot shows no variation in the detection rate with period, but again suffers from a clear bias in that long-period variability, more likely in less active stars, is much harder to identify observationally, for reasons of telescope scheduling and because less active stars have presumably less spot activity and therefore less modulation of their light curves.

Finally, in Figure 8 we plot the space velocities of the stars (the u and v components, corrected for solar motion as given by the Gliese catalog). The striking aspect of Figure 8 is the cluster of detected stars lying in the region -20 km s$^{-1} < u, v < 0$ km s^{-1}. Of 13 stars falling in this region, 12 are detected. Generally, stars close to the Sun in space motion are regarded as young stars belonging to the local supercluster (Eggen 1977) and are therefore more likely to be rapid rotators, whereas older stars have probably slowed down. The outlined region on Figure 8 indicates the location of the "young disk" stars on the *u-v* diagram as defined by Eggen. The lack of detections at large space velocities seems to agree with the widely held view that age, and thus probably rotation, is a major determinant of activity.

IV. SUMMARY

We have presented the results of a VLA survey of nearby flare stars and have summarized all published observations of M dwarf stars. Roughly 40% of all known nearby flare stars have been detected as radio sources. We believe that most of the detections are of flare emission rather than of quiescent emission, and, given the sporadic nature of the former, a larger fraction will turn out to be radio sources when longer observations are available. We observed several large flares during the survey, including the highest level of 6 cm flaring yet seen from this class of star.

To search for some stellar property which might "trigger" radio flaring, we have investigated the dependence of radio detection on other stellar properties for the larger sample of dM/dK stars. The significant correlations are with strong X-ray flux, with the presence of Hα in emission, and with age as reflected by the space motions of the stars. All of these effects have been expected, yet none of these properties guarantees that a star is a radio source (so far). Rapid rotation is held to be the most likely "trigger" for activity in general, but unfortunately most of the stars with known periods are very active stars, nearly all of which are radio sources; thus we must await period determinations for some of the less active stars before this effect can be determined in the data.

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Note added in proof.—The dM5.5e star WX UMa, undetected in three observations referred to in this paper, was detected as a strong source at both 20 and 6 cm in a fourth observation.

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