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SEARCHES FOR THE RADIO MILLIPULSES FROM M87 VIRGO A

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ABSTRACT

We have conducted a number of searches using a variety of techniques at three observatories in an attempt to confirm the observation by Linscott and Erkes of highly dispersed radio pulses from the vicinity of M87. Although the sensitivity of our search was greater than or equal to theirs, we found no pulses. We describe our technique, some of which involved the use of new instrumentation originally conceived for other purposes, but well-suited for a dispersed pulse search.
Subject headings: radio sources: galaxies — radio sources: variable

The recent discovery by Linscott and Erkes (1980, hereafter LE) of highly dispersed millisecond radio bursts from the direction of the radio source Virgo A in the galaxy M87 prompted a number of attempts at various observatories to confirm the discovery and make further studies of the pulses. We report here upon several of these attempts, the sensitivity of which ranged up to 10 times better than LE achieved, and one of which mimicked their method very closely. Several of the observing and signal-processing techniques we used are novel and had not been used directly for pulse searches before. Although tantalizing suspects were seen in our data, none were strong enough to confirm the discovery.

For all of the searches it was assumed (1) that the Virgo pulses had an intrinsic duration of 1 ms (the time resolution of LE's dynamic spectra), (2) that the pulses were dispersed by a cold plasma with a time-variable dispersion measure $1000 \leq \mathrm{DM} \leq 5000$ pc cm^{-3}, (3) that their radio spectral index was in the range $-1 \leq \alpha \leq 1$ from 400 to 1400 MHz, and (4) that if the pulses were periodic, the period is unknown and the pulse amplitude is strongly variable. The basic parameters of the searches are given in Table 1, and they are discussed below.

For the purpose of comparison we use the term *snapshot* to mean a two-dimensional matrix representing the received intensity across the receiver bandpass for a short time T. A snapshot is formed by a sequence of n power spectra with spectral resolution Δf, where each spectrum is averaged over a time $\Delta t = T/n$. A *pixel* is one element of the matrix, or a resolution cell with dimensions $\Delta t \Delta f > 1$. LE discovered the millipulses from M87 by noting linear tracks of intensity passing diagonally through their snapshots at a rate corresponding to a dispersion measure of 1000–5000 pc cm^{-3}.

Search I was made at Arecibo by continuous digital sampling of the detected outputs from 16 contiguous 250 kHz filter-bank channels, then plotting the 16 outputs simultaneously off-line in a manner analogous to a 16 channel chart recorder. These records were searched both by eye and by computer for pulses arriving at successively later times in lower-frequency channels. The sensitivities given in Table 1 assume a pulse width of 2.5 ms, equal to the dispersion sweep time across each filter channel (DM = 3300 pc cm^{-3}). The actual sensitivity for a narrower dispersed pulse will be reduced by the factor by which the actual pulse width is narrower.

Search II was made at Arecibo using a 1×8 bit auto- and cross-correlator built originally for decoding of Venus radar mapping signals. Two orthogonal circular polarizations were sampled over 0.5 MHz, and the autocorrelation functions obtained were transformed by an FPS 120B array processor. The resulting power spectra were plotted as snapshots in the same way as LE's discovery data. These records were searched by eye for dispersed pulses. The sensitivity of a single channel of this system is less than that of LE's by a factor of 1.23 because of the 1×8 bit quantization of the autocorrelator (Hagen and Farley 1973), but adding the orthogonal polarization power spectra together more than compensates for this loss of sensitivity.

Searches IIIa and IIIb were made at Arecibo by rapidly sampling the 0.5 or 1.25 MHz baseband mixed intermediate-frequency signal, then computing the power spectrum and plotting the intensity-frequency-time snapshot off-line. Part b of the search was designed to be as nearly equivalent to LE's as possible, but doing all processing in software. Faster tape drives permitted recording of a 40 ms snapshot every 300 ms, as compared with a 51 ms snapshot every 10 seconds which LE obtained. Thus our "duty cycle" was considerably higher. Equal amounts of data were recorded both on and off source at 430, 606, 1020, and 1400 MHz, but no pulses were found. The data were also processed to adjust the frequency resolution to optimize detection. For maximum signal-to-noise ratio the signal should fully occupy only one $\Delta f \Delta t$ pixel at a time. For example, at 1400 MHz in LE's snapshots a signal with DM = 3300 pc cm^{-3} sweeps across 17 of LE's Δf pixels in one Δt time-resolution interval. By adding together 17 adjacent Δf pixels, the signal increases by a factor of 17, whereas the rms noise increases by only $(17)^{1/2}$ giving an improvement in signal-to-noise ratio of about 4. In our searches this approach was used whenever possible. The improvement expected does, however, rely on assumptions (1) and (3) above.

TABLE 1

BASIC SEARCH PARAMETERS

Search	Participants	Telescope	Freq. (MHz)	Technique	Channels and bandwidth (n x KHz)	Total bandwidth (MHz)	Integration time (ms)	T_{sys} on Virgo (1) (Jy)	S_{lim} (2) (Jy)	S_{lim} / S_{LE} (3)	Telescope beamwidth	Time on source (min) (4)	Date (1979)
I	MMD, DCF	Arecibo	1400 606	filter bank	16x250 16x20	4 0.32	1 1	214 446	43 100	2.5 2.2	3′.5 10′	40 30	16 Jun 5 Aug
II	DBC, MMD	Arecibo	430	1x8-bit autocorrelator	2x256x2 (5)	2x0.5	1	550	239	1.15	10′	2	8 Sep 9 Sep
IIIa	MMD	Arecibo	606	direct i.f. sampling	128x4 256x2	0.5 0.5	1 2	446 446	223 223	1.0 1.0	10′ 10′	1.1 1.1	20 Aug 20 Aug
IIIb	THH	Arecibo	430 1020 1400	direct i.f. sampling	256x5 64x20 32x40	1.25 1.25 1.25	0.82 0.82 0.82	550 305 214	275 152 107	1.0 - 1.0	10′ 6′ 3′.5	0.4 0.4 0.4	22 Dec 22 Dec 22 Dec
IV	RE, JO	Westerbork	1400	2 filters and threshold detector	2x80	0.16	1	123	42	2.5	1°x23"	360	20 Aug
V	THH, JN, WS, GAEW	Effelsberg	1400	optical acoustical spectrometer	400x100	40	1	276	28	3.8	8′	120	24,26, 27,30 Jul 7 Aug 8 Aug
VI	THH, RE, JN, JO WS, GAEW	Westerbork	1400	optical acoustical spectrometer	2x100x100 (6)	2x10	1	123	12.3	8.7	1°x23"	120	16-18, Oct
LE	IL, JE	Arecibo	430 606 1400	Mark II VFFT (7)	256x5	1.25	0.82	550 446 214	275 223 107	1.0 1.0 1.0	10′ 10′ 3′.5	1 1 1	1,2 10 May

Notes:
1. System temperature with the telescope pointed at Virgo, expressed in Janskys.
2. Limiting sensitivity (rms noise in Janskys per channel).
3. Ratio of limiting sensitivity of the current search to the limiting sensitivity of LE.
4. In searches I through VI equal time was also spent observing off-source positions.
5. Right and left circular polarizations added after detection.
6. Orthogonal linear polarizations.
7. The Mark II VFFT is a digital processor capable of computing 1024-point complex Fast Fourier Transforms at data rates up to 10 MHz.

Two-dimensional autocorrelations of these time-frequency snapshots were computed and averaged to check for consistent low-level dispersed or periodic structure, but none was found.

Search IV was made at the Westerbork Synthesis Radio Telescope (WSRT) using two detected channels separated by 0.5 MHz, centered on 1400 MHz. Whenever a signal exceeding a preset threshold was received in the higher-frequency channel, an oscilloscope sweep was triggered, enabling the lower-frequency channel to be observed at a later time corresponding to the time of arrival delay due to dispersion between the two channels. No dispersed pulse events with amplitudes greater than expected from Gaussian noise statistics were observed.

Searches V and VI were made at the Effelsberg 100 m telescope and the WSRT using a new optical acoustical laser spectrometer (OAS) built at the Max-Planck-Institut für Radioastronomie based on a design by Cole (1973*a*, *b*). The OAS has 1024 100 kHz channels with a minimum time resolution of 0.5 ms. At 1400 MHz the sweep time across a 100 kHz bandwidth for a dispersed pulse with DM = 3300 pc cm^{-3} is 1 ms, so that the OAS is nearly perfectly matched for optimal signal-to-noise ratio for the expected Virgo pulses. Data were recorded on 35 mm film as a continuous intensity-modulated dynamic spectrogram in two modes. In the direct mode, the first-order diffraction pattern of the intermediate-frequency modulated laser light was imaged directly on film through a narrow slit at the film plane. The time resolution was determined by the slit width divided by the film transport speed past the slit. In the indirect mode the laser light was imaged on a Reticon photo-diode array which was "dumped" serially to an intensity modulated oscilloscope to produce a complete 1024 point spectrum as often as every 0.5 ms, which was recorded on film as a dynamic spectrum in the same way that solar burst spectra have been recorded for many years. The direct mode had the advantage of large dynamic range as a result of the logarithmic response of the film, and it avoided the irregular response and noise introduced by the photo diodes. The indirect method had the advantage of permitting some processing of the video signal for baseline removal before display, and the nonlinear response of the oscilloscope phosphor could be used to produce a sharp threshold below which no signal was recorded. Both methods were used on the telescope. Calibration showed that a swept signal whose signal-to-noise ratio in a single channel was 2 or better was easily detectable by scanning the developed film by eye.

On the Effelsberg telescope the full intermediate-frequency bandwidth of 40 MHz was recorded along with time and frequency calibration marks. The WSRT was used in the "tied array" mode where the separate intermediate-frequency channels from each of the 12 antennas are added together. This produces a knife-edge beam which is 23″ in right ascension and 1° in declination at 0^h hour angle increasing to 42″ × 1° at $+4^h$ hour angle with a position angle of +70°. Two 10 MHz wide orthogonal linear-polarization video signals were available before detection. They were separately mixed up to the passband of the spectrometer so that both polarizations were recorded twice (upper and lower sidebands of the up-converted signal) side by side on the film. A dispersed pulse with random, circular, or linear polarization with large Faraday rotation would appear as two V-shaped traces side by side on the film, one V for each polarization channel, and each leg of the V being its own reflection in the other up-converter sideband. This double redundancy recording method provides a large improvement in the ability to reject spurious traces or fortuitous alignments of noise peaks or film grain clumps. In no cases did we find any V-shaped traces which appeared simultaneously in both polarization channels.

One load of film would record for about 20 minutes, which at a rate of 1000 400-point spectra per second, yields $\sim 5 \times 10^8$ data points. Examining the film with a loupe proved tedious at best. A microfilm viewer was modified to accept a closed-circuit television camera so that the contrast and threshold of the images could be manipulated to enhance the pulse detectability, and the viewer could use both eyes at a comfortable distance.

It has been pointed out (Wright and Hankins 1980) that the 3$'$.5 beamwidth of the Arecibo telescope with which LE discovered the Virgo pulses includes nearly all of the Virgo galaxy including the jet and the position of a supernova observed in 1919 (Balanowsky 1922). In order to resolve where the pulses originated, we pointed the Westerbork telescope at eight adjacent positions across the galaxy and at the supernova position at the appropriate angle such that most of the galaxy was not included in the knife-edge beam. The narrow beam of the WSRT resolves the galaxy and consequently the system temperature on-source–to–off-source ratio was approximately half of the value obtained at Effelsberg and Arecibo, thereby enhancing the detectability by a factor of 2 over the other searches. Combining this factor, the channel bandwidth, and continuous recording in time, we estimate that the sensitivity of this phase of the search should have been from 6 to 10 times better than LE at 21 cm.

If the pulses LE observed were from an extraterrestrial source, they may have come from either a young, very sporadic pulsar or from some as yet not understood phenomenon. It is hard to contrive accidentally a signal with the characteristics they observed, especially the sweep rate which scales with frequency as f^3. On the other hand, we feel that we would easily have detected signals with the characteristics LE observed if they had occurred as often and with the same strength they reported.

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REFERENCES

Balanowsky, I. 1922, *Astr. Nach.*, **215**, 215.
Cole, T. W. 1973*a*, *Proc. IEEE*, **61**, 1321.
———. 1973*b*, *Ap. Letters*, **15**, 59.
Hagen, J. B., and Farley, D. T. 1973, *Radio Sci.*, **8**, 775.
Linscott, I. R., and Erkes, J. W. 1980, *Ap. J.* (*Letters*), **236**, L109 (LE).
Wright, G. A. E., and Hankins, T. H. 1980, *Science*, submitted.

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