THE VARIABLE RADIO–TO–X-RAY SPECTRUM OF THE MAGNETAR XTE J1810–197

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ABSTRACT

We have observed the 5.54 s anomalous X-ray pulsar XTE J1810–197 at radio, millimeter, and infrared (IR) wavelengths, with the aim of learning about its broad-band spectrum. At the IRAM 30 m telescope, we have detected the magnetar at ν = 88 and 144 GHz, the highest radio-frequency emission ever seen from a pulsar. At 88 GHz we detected numerous individual pulses, with typical widths ~ 2 ms and peak flux densities up to 45 Jy. Together with nearly contemporaneous observations with the Parkes, Nançay, and Green Bank telescopes, we find that in late 2006 July the spectral index of the pulsar was −0.5 ≲ α ≲ 0 (with flux density Sν ∝ να) over the range 1.4–144 GHz. Nine dual-frequency Very Large Array and Australia Telescope Compact Array observations in 2006 May–September are consistent with this finding, while showing variability of α with time. We infer from the IRAM observations that XTE J1810–197 remains highly linearly polarized at millimeter wavelengths. Also, toward this pulsar, the transition frequency between strong and weak scattering in the interstellar medium may be near 50 GHz. At Gemini, we detected the pulsar at 2.2 µm in 2006 September, at the faintest level yet observed, Kσ = 21.89 ± 0.15. We have also analyzed four archival IR Very Large Telescope observations (two unpublished), finding that the brightness fluctuated within a factor of 2–3 over a span of 3 years, unlike the monotonic decay of the X-ray flux. Thus, there is no correlation between IR and X-ray flux, and it remains uncertain whether there is any correlation between IR and radio flux.

Subject headings: pulsars: individual (XTE J1810–197) — stars: neutron

1. INTRODUCTION

Anomalous X-ray pulsars (AXPs) are neutron stars with long spin periods and extremely strong surface magnetic fields, the decay of which is largely responsible for their observed X-ray emission according to the magnetar model (Duncan & Thompson 1992). Of the dozen identified magnetars (including soft-gamma repeaters in addition to AXPs), half have also been detected at infrared (IR) wavelengths (see Woods & Thompson 2006, for a review of magnetar properties). While the IR fluxes of magnetars have been observed to vary (e.g., Hulleman et al. 2004), it is neither clear how these variations relate to changes in observed X-ray flux, nor what is the origin in detail of the IR radiation.

XTE J1810–197 is a transient AXP with period 5.54 s, first detected when its X-ray flux increased ~ 100-fold compared to the historical level maintained for at least 24 years (Halpern & Gotthelf 2005). Four years after the outburst, its X-ray flux has decreased nearly to the quiescent level (Gotthelf & Halpern 2007). It was also detected in the IR in 2003 October (Israel et al. 2004), and was observed 5 months later to be 60% fainter (Rea et al. 2004).

XTE J1810–197 is the only magnetar known to emit radio waves (Halpern et al. 2005). This emission is entirely pulsed (Camilo et al. 2006; Helfand et al. 2007), is aligned in phase with the X-ray pulsations (Camilo et al. 2007a), and is highly polarized, in some respects being similar to that of ordinary young radio pulsars (Camilo et al. 2007b). However, unlike in ordinary pulsars, the radio emission appears to be transient, the average flux density varies intrinsically by factors of up to ~ 3 on approximately daily timescales, and the pulse profiles vary as well (Camilo et al. 2007d). Even early 2007, the average radio flux density was a factor of ~ 20 lower than when pulsations were first observed 1 yr earlier (Camilo et al. 2007a). Also, unlike the vast majority of ordinary pulsars, XTE J1810–197 has a radio spectrum consistent with being flat (α ~ 0; Sν ∝ ν0), over the large frequency range 0.7 ≲ ν ≤ 42 GHz (Camilo et al. 2006).

The radio window provides a new opportunity for learning about the emission mechanism(s) of magnetars. For instance, an extrapolation of the radio spectrum of XTE J1810–197 exceeds its IR flux, so that the radio and IR emission could have the same origin. However, the shortest radio wavelength at which a detection had been reported (7 mm) is 3000 times larger than the IR wavelengths, so that coverage at shorter radio wavelengths is desirable, also to provide further constraints on the radio emission. Variability in the IR and comparison with radio variability would also be of great interest, but only two IR observations have been reported, and they predate the discovery of radio pulsations.

With these objectives in mind, we report here on observations of XTE J1810–197 at the IRAM telescope, which has the capability to detect pulsars in the 1–3 mm range, on simultaneous radio observations, and also on a new IR observation at Gemini, along with analysis of archival IR observations from the Very Large Telescope (VLT).

2. OBSERVATIONS, ANALYSIS, AND RESULTS

2.1. Millimeter wavelengths: IRAM
We observed XTE J1810–197 at the IRAM 30 m telescope in Pico Veleta, Spain, during 2006 July 19–21. We recorded four intermediate frequencies (IFs) simultaneously. These correspond to two linear polarizations (rotating with telescope elevation, but parallel and perpendicular to the ground at the inputs to the receivers, here designated H and V, respectively) at one of two possible pairs of frequencies (cryostats AB, with receivers operating at nominal frequencies of 100 and 230 GHz, or CD, at 150 and 270 GHz). We used the AB receivers on July 19 and 21, and CD on July 20. We tuned all receivers in double side-band mode, with the IFs for the 100 GHz receivers centered at 1.5 GHz with 1 GHz bandwidth, and those for all others centered at 4 GHz with 2 GHz bandwidth. At the lowest frequency used, we set the local oscillator to 88.5 GHz, thereby recording combined signals from 87 ± 0.25 GHz and 90 ± 0.25 GHz. For the lowest frequency of the CD cryostat pair, signals were recorded from 140 ± 0.5 GHz and 148 ± 0.5 GHz, for a central sky frequency of 144 GHz. The other central frequencies used were 224 and 264 GHz. Dispersion is irrelevant at these frequencies, and we sampled the total power IF signals every 0.5 ms using a 16-bit analog-to-digital converter, with the output recorded in VME modules using a custom configuration built by J.P. and colleagues at IRAM. The data stream containing the sampled power from the 4 IFs and a time stamp, referenced to the Observatory time standard and ultimately to UTC, was recorded to disk for off-line analysis. A typical observing session of 5 hr consisted of sets of pointing, focus, and flux-calibration scans (on Mars, Jupiter, or Venus), interspersed with four scans on XTE J1810–197, each about 1 hr in length, at elevations of 12° ≤ ε ≤ 39°. Weather conditions were variable, and the sensitivity varied on each night by up to 20% at 88 GHz and 20% at 144 GHz.

Due to large changes in the atmospheric conditions at IRAM on timescales of tens of seconds to several minutes, folding each XTE J1810–197 time-series modulo the 5.54 s pulse period (using the contemporary radio ephemeris; §2.2), plotted as a function of frequency (top) and date (bottom). For each combination of frequency and telescope we use a unique symbol that is common to both plots. These symbols can be fully decoded by referring to Table 4. With the exception of the VLA measurements whose flux density uncertainties are recorded in Table 4 the fractional uncertainties are ~ 25%.

![Image](55x438 to 171x730)

**FIG. 1.** XTE J1810–197 at IRAM at a central frequency of 88.5 GHz on 2006 July 19 (left) and 144 GHz on July 20 (right). Only signal from one of the polarizations (H) is folded in these plots. The variation with time of the signal strength (bottom plots) is likely mainly due to interstellar scintillation (see §2.1). The white spaces correspond to times during which the telescope was not pointed at XTE J1810–197, and the pulse profiles displayed with 256 phase bins are shown twice in each panel.

**TABLE 1**

| Date (MJD) | $S_{sys}^{\nu_1}$ (Jy) | $S_{sys}^{\nu_2}$ (Jy) | $S_{sys}^{\nu_1}$ (Jy) | $S_{sys}^{\nu_2}$ (Jy) |
|-----------|------------------------|------------------------|------------------------|------------------------|
| 53935     | 692–783                | 775–843               | 5640–785               | 6430–8960              |
| 53936     | 1780–2590              | 1640–2420             | 23000–53400            | 23400–55000            |
| 53937     | 702–862                | 775–942               | 4290–10700             | 4940–12100             |
| 54079     | 632–650                | 725–729               | 2130–2270              | 2400–2560              |
| 54118     | 660–693                | 757–815               | 2650–2810              | 2800–3000              |
| 54172     | 608–725                | 706–832               | 2250–2910              | 2440–2800              |
| 54180     | 582–631                | 687–740               | 1900–2080              | 2080–2290              |
| 54207     | 590–642                | 698–750               | 2700–3040              | ...                   |

**NOTE.** On MJD 53936, center frequencies were $\nu_1 = 144$ and $\nu_2 = 264$ GHz, respectively; on all other days, 88 and 224 GHz. For each frequency, we provide the range of measured system equivalent flux density separately for the “horizontal” (H) and “vertical” (V) polarizations (see §2.1). These were all corrected for air mass, measured hourly. The bandwidths used were 1 GHz at 88 GHz and 2 GHz at other frequencies.

![Image](173x438 to 291x729)

**FIG. 2.** Pulse-averaged flux densities of XTE J1810–197 across the frequency range 1.4–144 GHz obtained over a period of 2.5 days (see §§2.1 and 2.2), plotted as a function of frequency (top) and date (bottom). For each combination of frequency and telescope we use a unique symbol that is common to both plots. These symbols can be fully decoded by referring to Table 4. With the exception of the VLA measurements whose flux density uncertainties are recorded in Table 4 the fractional uncertainties are ~ 25%.
suring the area under the profiles and dividing by the pulsar frequencies. 

144 GHz (2.1 mm; Fig. 1), and was not detected at higher frequencies. In the V polarization, the pulsar was not detected at only the lower frequency of each pair (see § 2.1). Unless otherwise specifically given, the fractional flux density uncertainties are about 25%.

| Date (MJD/yymmdd) | Time (hr) | Frequency $\nu$ (GHz) | $S_\nu$ (mJy) | Telescope |
|-------------------|-----------|-----------------------|----------------|-----------|
| 53862.4/060507    | 0.2       | 1.4                   | 9.8 ± 0.4      | VLA       |
| 53862.4/060507    | 0.2       | 8.5                   | 5.7 ± 0.2      | VLA       |
| 53873.3/060518    | 0.6       | 1.4                   | 3.3 ± 0.2      | VLA       |
| 53873.3/060518    | 0.6       | 4.9                   | 3.5 ± 0.3      | VLA       |
| 53889.4/060603    | 0.7       | 1.4                   | 8.1 ± 0.5      | VLA       |
| 53889.4/060603    | 0.7       | 4.9                   | 6.2 ± 0.2      | VLA       |
| 53894.6/060608    | 7         | 1.4                   | 8.5 ± 0.2      | ATCA      |
| 53894.6/060608    | 7         | 2.4                   | 8.5 ± 0.2      | ATCA      |
| 53897.5/060611    | 0.7       | 1.4                   | 10.4 ± 0.5     | VLA       |
| 53897.5/060611    | 0.7       | 4.9                   | 7.5 ± 0.2      | VLA       |
| 53905.5/060619    | 0.3       | 1.4                   | 8.0 ± 0.9      | VLA       |
| 53905.5/060619    | 0.3       | 4.9                   | 8.0 ± 0.2      | VLA       |
| 53906.1/060620    | 0.9       | 0.35                  | 9.4            | GBT       |
| 53935.5/060671    | 0.3       | 1.4                   | 4.9            | Parkes    |
| 53935.5/060671    | 0.6       | 1.4                   | 2.6            | Parkes    |
| 53935.6/060671    | 2.3       | 6.6                   | 0.7            | Parkes    |
| 53935.7/060719    | 0.4       | 1.4                   | 1.9            | Parkes    |
| 53935.9/060719    | 0.2       | 1.4                   | 1.8            | Nançay    |
| 53935.9/060719    | 3.6       | 1.4                   | 1.2            | IRAM      |
| 53936.0/060720    | 1.5       | 9.0                   | 0.7            | IRAM      |
| 53936.1/060720    | 0.9       | 19.0                  | 1.0            | IRAM      |
| 53936.3/060720    | 0.7       | 1.4                   | 2.0 ± 1.0      | VLA       |
| 53936.3/060720    | 0.7       | 4.9                   | 1.4 ± 0.2      | VLA       |
| 53936.9/060720    | 4.7       | 144.0                 | 1.2            | IRAM      |
| 53937.9/060721    | 1.7       | 88.5                  | 1.2            | IRAM      |
| 53958.2/060811    | 0.7       | 1.4                   | 6.0 ± 0.6      | VLA       |
| 53958.2/060811    | 0.7       | 4.9                   | 2.7 ± 0.2      | VLA       |
| 53983.2/060905    | 0.7       | 1.4                   | 3.4 ± 0.6      | VLA       |
| 53983.2/060905    | 0.7       | 4.9                   | 1.1 ± 0.3      | VLA       |
| 53991.8/060913    | 0.3       | 1.4                   | 1.6            | Nançay    |
| 53992.7/060914    | 0.2       | 1.4                   | 1.6            | Nançay    |
| 54069.5/061130    | 1.1       | 1.4                   | 0.4            | Nançay    |
| 54069.9/061130    | 0.6       | 0.35                  | 1.6            | GBT       |
| 54078.5/061209    | 0.7       | 1.4                   | 0.7            | Nançay    |
| 54079.5/061210    | 3.6       | 88.5                  | 0.22 ± 0.11    | IRAM      |
| 54118.4/070118    | 4.0       | 88.5                  | < 0.1          | IRAM      |
| 54172.2/070313    | 4.5       | 88.5                  | < 0.1          | IRAM      |
| 54180.2/070321    | 4.0       | 88.5                  | < 0.1          | IRAM      |
| 54207.2/070417    | 3.2       | 88.5                  | 0.34 ± 0.17    | IRAM      |
| 54209.2/070448    | 0.8       | 1.4                   | 1.7            | Nançay    |

Note.— We list here all our simultaneous dual-frequency observations, along with selected others, ordered by date. At IRAM, the frequency pairs were 88.5 and 224 GHz, or 144 and 264 GHz. The pulsar was detected at only the lower frequency of each pair (see § 2.1). Unless otherwise specifically given, the fractional flux density uncertainties are about 25%.

We then Fourier transformed the time series and clipped the Fourier amplitudes of the strong 1 Hz harmonics as well as the prominent 50 and 100 Hz signals. Finally, we inverse Fourier transformed the data to regenerate mostly interference-free profiles. We believe that these signals, at 50 and 100 Hz, as well as many harmonics of 1 Hz, are locally-generated compressor-related interference.

In order to combat these issues, we filtered the data in two ways. First, to remove the low-frequency noise below ~ 0.1 Hz (due primarily to the changing atmosphere), we high-pass-filtered each time series using a 3rd-order Bessel filter. We then Fourier transformed the time series and clipped the Fourier amplitudes of the strong 1 Hz harmonics as well as the prominent 50 and 100 Hz signals. Finally, we inverse Fourier transformed the data to regenerate mostly interference-free time series, which we then folded. After filtering, the V polarization sensitivity to pulsed signals remained significantly worse than that of the H polarization. The pulsar was not detected in the V polarization. In the H polarization, the pulsar was clearly visible on both days at 88 GHz (3.4 mm) and at 144 GHz (2.1 mm; Fig. [1]), and was not detected at higher frequencies.

We determined the period-averaged flux density by measuring the area under the profiles and dividing by the pulsar period. This was converted to an absolute Jansky scale using the hourly flux-calibration scans, from which the system equivalent flux density $S_{sys}$ was calculated for each frequency and polarization. The off-pulse profile rms then corresponds to $S_{sys}(BT)^{-1/2}$ for a bandwidth $B$ and an integration time $T$, where $S_{sys}$ is corrected for air-mass attenuation $\exp(-\tau/\sin\epsilon)$, and $\tau$ is the measured zenith opacity. The ranges of $S_{sys}$ obtained for each observation are listed in Table [1].

It is clear from Figure [1] that the observed flux density can vary greatly with time. Changing weather conditions and elevation account for only up to 10% of this variation in the July 19 data, displayed in the left panel of the figure (see Table [1]). A great portion of the variation is most likely caused by interstellar scintillation (see Camilo et al. [2006]). As an average, we estimate the flux density to have been 1.2 mJy at both 88 and 144 GHz, with a fractional uncertainty on the absolute values of about 25% (see Fig. [2] and Table [2]). In order to calculate approximate flux density limits for non-detections, we assume a threshold signal-to-noise ratio of 5 and a pulse duty cycle of 2%. For example, on July 19 we...
Fig. 4.— Average pulse profiles of XTE J1810–197 obtained at frequencies spanning 1.4–144 GHz over a period of 1.5 days, at Parkes, GBT, and IRAM. Each profile is labeled by the telescope used, the date (MJD) of the observation, the central frequency and, in parentheses, the bandwidth and integration time used. IRAM profiles include data from only one polarization (see § 2.1), and are displayed with 256 phase bins. Parkes and GBT profiles have 1024 bins. Profiles were aligned by eye such that the peak pulse component arrives near phase 0.15. The FWHM of these profiles are, in order of increasing frequency, 4.2, 2.2, 1.7, 1.6, 1.3, and 1.3% of the pulse period.

obtain $S_{224} \lesssim 0.9$ mJy.

The observed flux density was so great on July 19 toward the end of the third scan (Fig. 1) that we were able to detect numerous individual pulses from XTE J1810–197 at 88 GHz. On this day we detected single pulses with signal-to-noise ratio $>4$ from about 15% of all rotations of the neutron star (Fig. 3). The largest pulses had a peak flux density of $\sim 45$ Jy, comparable to the strongest celestial sources known at 3 mm with the exception of the Sun, Jupiter, and Venus (although only for $\sim 1$ ms out of every $\sim 5$ s). On July 21 we also detected single pulses at 88 GHz.

Following these detections, we monitored the pulsar at 88/224 GHz on five occasions between 2006 December and 2007 April, using identical observing parameters. These latter observations were done in winter and early spring, under better weather conditions (Table 1). The pulsar was detected on two of these occasions, at 88 GHz in the H polarization, in December and April, with $S_{88} = 0.2–0.3$ mJy (see Table 2). In 2007 April, $S_{224} \lesssim 0.4$ mJy.

2.2. Radio: Parkes, Nançay, GBT, VLA, and ATCA

Because the intrinsic flux density and pulse profile of XTE J1810–197 vary on $\sim 1$ day timescales, determination of a spectral index ideally requires simultaneous multi-frequency observations. We therefore observed at Parkes, Nançay, the Green Bank Telescope (GBT), and the Very Large Array (VLA) on 2006 July 19–20, nearly simultaneously with IRAM. Table 2 lists these and all dual-frequency observations at the VLA and the Australia Telescope Compact Array (ATCA). The methods used have been described elsewhere (see Camilo et al. 2006 for Parkes and GBT; Camilo et al. 2007a for Nançay and VLA; Helfand et al. 2007 for ATCA).

The 1.4 GHz flux density decreased over a period of a few hours shortly before the first IRAM observation (Fig. 2 and Table 2). The average pulse profiles during these different flux states were identical (we show the first one in Fig. 4), unlike an observation in 2006 September with sudden simultaneous flux and profile changes (Camilo et al. 2007a).

The nominal flux density of the pulsar at 19 GHz was slightly greater than at 9 GHz (see Fig. 2). However, the observed flux at $\nu \gtrsim 9$ GHz varies on short timescales due to interstellar scintillation (Camilo et al. 2006; Fig. 1), and this may bias somewhat those flux densities obtained here (i.e., 1 hr does not correspond to many scintles).

Using simultaneous 1.4 and 4.9 GHz observations, we measured a spectral index $\alpha = -0.3 \pm 0.4$. The large uncertainty is due to the uncertain 1.4 GHz flux density, the smallest ever measured at the VLA for the magnetar. On a total of nine occasions we have used accurately flux-calibrated simultaneous dual-frequency data to determine the spectral index of XTE J1810–197, shown in Figure 5. From this, it is apparent that the radio spectrum, averaged over all its pulse profile components, varies, and there is a hint that since late 2006 July it might have become steeper (at least in the 1.4–4.9 GHz range). This appears to be supported by estimates of $\alpha$ obtained from near-simultaneous multi-frequency observations...
pulsed flux measurements at GBT; those shown in Figure 5 for two epochs in 2006 October and November have \( \alpha \lesssim -0.5 \), while before mid-2006, \( \alpha > -0.5 \) \cite{Camilo2006}. We have also extended the range of frequencies over which the magnetar has been detected, with two GBT observations at 0.35 GHz. Together with observations at other frequencies within half a day of these (Table 2), we obtain \( \alpha = 0 \) in 2006 June, but \( \alpha = -1 \) in 2006 November. This further supports the notion that the spectrum of XTE J1810–197, while variable with \( \alpha \) ranging between approximately 0 and \(-1\), may have become generally steeper after mid-2006.

### 2.3. Infrared: Gemini and VLT

We obtained a near-IR \( K_s \)-band (2.15 \( \mu \)m) observation of XTE J1810–197 at Gemini-North on 2006 September 14. We used the adaptive optics (AO) system Altair with the near-IR imager NIRI \cite{Hodapp2003}. With this configuration, the 1024 \( \times \) 1024 pixel Aladdin InSb array covers 22 \( \times \) 22 arcsec\(^2\) at 21.9 mas pixel\(^{-1}\). For photometric calibration, as well as the astrometric analysis described in \cite{Helfand2007}, we also analyzed \( K_s \)-band observations taken on 2003 September 18 with NIRI on Gemini without the AO system (for which the detector covers 2 \( \times \) 2 arcmin\(^2\) at 117 mas pixel\(^{-1}\); 19 minute exposure time).

For comparison, we analyzed observations taken at the VLT using the AO system NAOS with the CONICA camera \cite{Lenzen2003,Rousset2003}. NAOS-CONICA also uses a 1024 \( \times \) 1024 Aladdin detector, covering 27 \( \times \) 27 arcsec\(^2\) at 27.0 mas pixel\(^{-1}\). These observations were obtained in 2003 October \cite{Israel2004}, 2004 March \cite{Rea2004}, and 2004 September (on two nights, previously unpublished). We summarize in Table 3 the IR observations of XTE J1810–197 analyzed here in detail.

All observations were taken in a similar way, with images taken at dithered positions, and each image consisting of one or more co-added exposures, with the counts in each exposure determined from the difference between series of readouts before and after the actual integrations. We reduced all observations in an identical fashion, using the Munich Image Data Analysis System (MIDAS) or the Image Reduction and Analysis Facility (IRAF). We corrected for pixel-to-pixel sensitivity variations using sky flats constructed from the images themselves, aligned the images to integer pixel boundaries, and took averages. The 2003 October data had uncorrected horizontal “banding” that was not removed by the flat-fielding process. We removed this feature using the median value for each data row before stacking images. In \cite{Helfand2007}, we used the 2004 and 2006 observations in Table 3 to confirm that the IR counterpart has the same proper motion as that measured from radio VLBA observations.

In Figure 6 we compare the final VLT image from 2004 March with our new Gemini image from 2006 September. Over this 2.5 yr period, the IR counterpart has moved about one pixel to the south relative to local stars due to its proper motion, and clearly it has faded. For a quantitative analysis of all the images, we used the DAOPHOT II package \cite{Stetson1987}, running inside MIDAS and IRAF, to derive instrumental magnitudes by fitting a model point-spread function (PSF) for stars on the average images. Following the recommendations of \cite{Stetson1987}, the PSF was derived from brighter stars in an iterative fashion, where in each iteration nearby fainter stars are removed with the current best model. For a well-matched model PSF, with minimal residuals, we chose a Lorentzian analytical base, and linear dependence of the shape on position.

We calibrated our instrumental magnitudes relative to the 2MASS \cite{Skrutskie2006} in two steps. First, we derived offsets for 2MASS stars measured in the wider 2003 September NIRI image. We found that a constant offset gave a good fit, with the rms residual of 0.06 mag being only slightly larger than the typical 2MASS measurement error of \( \sim 0.05 \) mag for the stars we used.

We then transferred the photometry to the AO images using fainter stars. For this step, we found that the stars had a large scatter around the mean, of up to about 0.1 mag, with no obvious dependencies on brightness, position, or proximity to the guide star used. Likely, this reflects the general difficulty of doing reliable photometry on AO-corrected images. This was a particular problem for the 2004 March data, perhaps related to the fact that it had the best AO correction.

The \( K_s \) magnitudes thus obtained for XTE J1810–197 are listed in Table 3. The values for 2003 October and 2004 March are consistent with those reported by \cite{Israel2004} and \cite{Rea2004}, respectively, although our uncertainties (dominated by photon noise) are a factor of 2 larger (we do not understand the reason for this discrepancy). We also searched for intra-night variations in the 2004 March data, by considering the observation in two separate 18 minute segments, finding a magnitude difference of \( 0.11 \pm 0.23 \). We have therefore found no evidence for variations on \( \sim 1 \) hr or \( \sim 1 \) day timescales, at the \( \gtrsim 20\% \) level, but the IR brightness of XTE J1810–197 evidently fluctuated, with no clear trend, by a factor of \( 2 \)–\( 3 \) within the 3 year period covered by the (sparsely sampled) observations. Using the \( K_s \)-band zero point of \cite{Cohen2003}, the Gemini mea-
measurements in 2006 September correspond to a flux density of $1.17 \pm 0.17 \, \mu$Jy. If $A_V = 3.6$ (Halpern & Gotthelf 2005), then $A_K = 0.40$ (Schlegel et al. 1998), so that the de-reddened flux is 1.45 times larger, 1.69 $\pm 0.25 \, \mu$Jy.

3. DISCUSSION

The notable detection of XTE J1810–197 at frequencies of 88 and 144 GHz with IRAM is a record among pulsars (see Morris et al. 1997, for previous highest-frequency detections). This magnetar has now been detected at radio—millimeter wavelengths spanning a factor of 400. The spectrum over this expanse is flat compared to that of most pulsars (measured over a narrower range), but it is difficult to make a definitive quantitative statement: (1) as for ordinary pulsars (e.g., Kramer et al. 2003), individual phase components of the pulse profile may have differing spectra; (2) at high frequencies ($\gtrsim 9$ GHz) there is considerable variability in measured flux density due to interstellar scintillation; (3) the intrinsic flux varies with time; (4) the spectrum also apparently varies with time (see Fig. 5); and (5) the intrinsic spectrum need not be represented by a single power law.

The only simultaneous multi-frequency detections among those summarized in Figure 2 were the ones at the VLA (1.4 and 4.9 GHz), and 1.4 GHz at Nançay along with 88 GHz at IRAM. The spectral index obtained from the first pair is $\alpha = -0.3$, while from the second, $\alpha = -0.1$, in both cases with substantial uncertainties and also suffering from some of the problems noted above. Attempts to infer $\alpha$ from other measurements collected within a period of 2.5 days (see Fig. 2), also suffered from such problems. (See also Fig. 5). With the foregoing caveats in mind, we summarize the situation thus: before 2006 August, the pulse-averaged spectrum of XTE J1810–197 over the range 1.4–144 GHz could be usefully described by a single spectral index in the range $-0.5 \lesssim \alpha \lesssim 0$, with some time variability observed. Since then, the spectrum has apparently steepened, with $-1.0 \lesssim \alpha \lesssim -0.5$.

In retrospect, the flux of the pulsar started changing dramatically around mid 2006 July, near the time of the first IRAM observations. This was accompanied by a change in the character of pulse profile variations, as well as large torque variations (see Camilo et al. 2007a). The flux density at 1.4 GHz by early 2007 was generally quite low ($\gtrsim 0.5 \, \mu$Jy) — although fluctuations continue: see the last entry in Table 2. Together with a moderate spectral index of $\alpha \lesssim -0.3$, this can account for the non-detections at $\gtrsim 88$ GHz in 2007 (Table 2).

The average pulse profiles of XTE J1810–197 observed during 2006 July 19–20 and spanning 1.4–144 GHz are shown in Figure 4. The profiles at 6.6–19 GHz are very similar, while in all 1.4 GHz observations on this date the “precursor” component is absent (phase 0.85 in the figure). This is unexpected, because the Parkes 1.4 GHz observations bracketed in time that at 6.6 GHz, ensuring that the differences observed between the pulse profiles were not caused by a global change in the profile. Rather, the absence of the precursor at 1.4 GHz may point on this day either to an extremely positive spectral index for that component ($\alpha > 1$), or to absorption of the 1.4 GHz radiation along the line of sight at the location in the magnetosphere corresponding to this pulse phase.

The absence of the precursor at 88 GHz may be explained by a spectrum over 19–88 GHz steeper than that of the main component by $\Delta \alpha \lesssim -0.7$. In making this estimate we assumed that roughly half of the precursor power would be present in each of the H and V polarizations. This follows from a computation of the polarimetric Stokes parameters as they would appear for the IRAM observations, under the assumption that the precursor was polarized at millimeter wavelengths as it was earlier at 1.4 GHz (see Camilo et al. 2007b). A similar computation for the main profile component using the (different) absolute position angle of linear polarization observed at 1.4–8.4 GHz (Camilo et al. 2007b), shows that the vast majority of its power in the IRAM observations should be present in the H polarization, as is indeed the case (§ 2.1). This provides evidence that XTE J1810–197 remains highly linearly polarized at wavelengths as short as 2 mm. For comparison, some ordinary pulsars appear to depolarize significantly with decreasing wavelength, down to the limit of the observations at 1 cm (Xilouris et al. 1996). However, separate profile components can evolve differently with wavelength. Karastergiou et al. (2005) consider a model where orthogonal polarized modes have different spectra, leading naturally to some highly polarized components with flat spectra, down to 10 cm wavelength. Also, several young pulsars remain highly polarized down to the limit of the observations at 3.5 cm (Johnston et al. 2004). It is therefore possible that in this respect XTE J1810–197 differs from ordinary young pulsars more in having a flat spectrum all the way down to 2 mm, which enables us to make the measurements, than in remaining highly polarized at those wavelengths (see also Camilo et al. 2007b). In any case, these two features may not be independent.

As seen clearly in Figure 1, the flux density of XTE J1810–197 observed at millimeter wavelengths through a bandwidth of 1–2 GHz varies by factors of a few on timescales of $\sim 1$ hr. Most of this variation is likely caused by interstellar scintillation (§ 2.1). The surprise is not that the received flux varies, but that it varies so relatively little. Qualitatively, the flux modulation for these IRAM observations is much smaller than that observed at 42 GHz, and more comparable to that observed at 14–19 GHz (cf. Camilo et al. 2006). Perhaps for this object, the transition between strong and weak interstellar scattering (at which the flux modulation peaks; see, e.g., Lorimer & Kramer 2005) is about 50 GHz. Detailed analysis of scintillating behavior for XTE J1810–197 will be presented by Ransom et al. (in preparation).

The single pulses seen from XTE J1810–197 at 88 GHz on 2006 July 19 (Fig. 3) appear qualitatively similar to those observed at 2 and 42 GHz about 2 months earlier (Camilo et al. 2006). In particular, they are narrow (a few ms), wander about with no obvious phase coherence from rotation to rotation, and gradually build up the much wider average profile. Also, some particularly strong pulses are emitted from rotational phases at which the average pulse is weak or not detectable, implying significantly different pulse energy distributions at different phases. A detailed treatment of single-pulse behavior from XTE J1810–197 will be presented elsewhere.

With the detection of XTE J1810–197 down to 2 mm wavelength, and shortward of 2.2 $\mu$m, there remains a factor of 1000 in wavelength where it is undetected (Wang et al. 2007 report upper limits at 24, 8, and 4.5 $\mu$m). As discussed earlier, the radio–to–millimeter spectrum is somewhat uncertain, and is variable, but it is flat enough that the radio spectrum extrapolated to IR wavelengths exceeds the IR fluxes (possibly by a very large amount; see Fig. 7). Therefore, it is possible that the radio spectrum steepens smoothly to join the IR. Contemporaneous detections in several IR bands would be useful to delineate the shape of the spectrum in this region. Similarly, detection of IR pulsations from XTE J1810–197 would be of great help in pinning down the emission mechanism, but this
nant cyclotron scattering in the magnetosphere can reproduce the spectrum using one surface temperature and one magnetization of X-ray blackbody photons can only produce high-energy power-law tails, not low-energy ones.)

Rea et al. (2004) noted that the IR and X-ray flux from XTE J1810–197 had both decreased by a factor of about 2 within a period of 5 months (see the first two observations in Table 3). They considered that a fossil disk reprocessing some X-rays might account for this correlation. However, we have shown that the IR emission from XTE J1810–197 fluctuated, rather than following a monotonic decreasing trend (§ 2.3). In 2006 September, it was a factor of about 2 fainter than when observed by Rea et al. (2004) 2.5 years before (Table 3). For comparison, the X-ray flux decreased monotonically by a factor of ∼ 20 in the same period (Gottlieb & Halpern 2007). Therefore, the IR and X-ray fluxes are not simply correlated.

Four AXPs, including XTE J1810–197, have displayed IR variations, although no general trend is evident thus far. In 1E 2259+586, following an X-ray outburst and accompanying IR increase, both decayed similarly and the IR flux reached the quiescent level after ∼ 1 yr (Tam et al. 2004). In 1E 1048.1–5937, large IR variations are not correlated with the spin-down rate, but may be anticorrelated with the X-ray flux (Durant & van Kerkwijk 2005). And in 4U 0142+61, although the IR, optical, and X-ray fluxes (and spectra) all vary, including IR variations of over a magnitude on a timescale of days, there are no clear correlations (Durant & van Kerkwijk 2006). In XTE J1810–197, the latest IR flux is also the faintest yet observed, and the presently observed spin-down rate is the smallest on record (Camilo et al. 2007a). The previous IR observations, brighter and showing some variability (Table 3), all took place within 1.8 yr of the original large X-ray outburst (Ibrahim et al. 2004). It is therefore possible to postulate that the latest IR detection corresponds to some sort of quiescent level, much like the star has approximately reached in X-rays (Gottlieb & Halpern 2007), while the earlier observations reflected at least in part transient responses from an active magnetar, related to the outburst that led in the first place to the discovery of XTE J1810–197. However, the sampling of the IR observations is limited, and no clear conclusion can yet be reached.

Likewise, we do not yet know whether the IR and radio fluxes are correlated. The original radio detection, in 2004 January, had a flux density at 1.4 GHz of 4.5 mJy (Halpern et al. 2005); at the time of the latest IR observation in 2006 September, this was near 1.6 mJy (Table 3); and between 2006 February and September, the flux density ranged between 13 and 1 mJy, with day-to-day fluctuations by factors of up to ∼ 3 and a general downward trend (Camilo et al. 2007a). At least in 2006, therefore, the radio flux fluctuated by a greater factor than did the IR between 2003 and 2006. But given the limited IR and nearly non-existent simultaneous radio–IR sampling, it remains possible that the fluxes in these two bands may be related. Simultaneous IR and radio observations sampling a variety of timescales should settle this question.

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