# LONG-TERM VARIATIONS OF THE COMPACT RADIO SOURCE SGR A* AT THE GALACTIC CENTER

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ABSTRACT. We investigate the long-term flux density variations of the compact radio source Sgr A* at the galactic center by combining recent VLA observations with previous Green Bank interferometer data. We present radio flux density light-curves for Sgr A* at 20, 11, 6 and 3.7 cm from 1974 to 1987. Long-term variability with a timescale of at least 5 years is seen at 20 cm and there is evidence for more rapid variations at the shorter wavelengths. The variability timescales at 20, 11 and 6 cm fit the $\lambda^2$ scaling predicted by the theory of refractive scintillation suggesting that the variability could be due to this cause. However, the timescales are relatively short, implying an unusually high velocity in the scattering screen. The modulation index of the variability is large and relatively independent of wavelength.

## 1. INTRODUCTION

Sgr A* is a very compact nonthermal radio source at the center of the Galaxy. It is surrounded by the thermal Sgr A West radio source with three spiral features extending over 2 × 3.6 parsecs (Ekers *et al.* 1983). Here we consider the flux variability of Sgr A* and investigate if it could be caused by refractive scintillation due to scattering in the medium surrounding the galactic center. The theory of refractive interstellar scintillation is fairly well-developed at the present time (Rickett, Coles and Bourgois 1984, Blandford and Narayan 1985, Rickett 1986, Blandford, Narayan and Romani 1986, Cordes, Pidwerbetsky and Lovelace 1986) and makes clear predictions regarding the amplitude and timescale of variability. We compare these predictions with the observations.

## 2. OBSERVATIONS AND DATA COLLECTION

We have observed Sgr A* for about seven years with the VLA at 20 and 6 cm. Combining the VLA measurements with NRAO Green Bank interferometer observations at 11 and 3.7 cm, we have data at four wavelengths covering 14 years,



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but there is minimal overlap among the different wavelengths. Only observations capable of separating out the compact source from the bright, extended complex of emission are useful since otherwise there will be an unpredictable contribution to the measured flux density depending on the actual resolution and the sidelobe structure. This circumstance means that only data with resolution falling in the window between confusion from the nearby H II region (3″) and the apparent size of Sgr A* (which is $\lambda$ dependent, *e.g.*, Lo 1987 and eq. 1 below) can be used.

The most recent VLA observations at 20 and 6 cm were on Sept. 26, 1987 in the A configuration. Measurements were made in the visibility domain, and were referred to 3C286 as the flux density calibrator. At 20 cm the flux density was confirmed by using a two-dimensional guassian fit (IMFIT in AIPS). Other VLA data were collected from various published and unpublished sources. The 20 and 6 cm data, mostly from the VLA, are listed in Table 1. An earlier observation with the Jodrell Bank 23.7-km interferometer is also included.

In addition to the VLA data, we collected previous 11 and 3.7 cm flux densities measured with the NRAO 35-km interferometer at Green Bank (Balick and Brown 1974, Brown and Lo 1982, Backer 1982). These data are listed in Table 2.

Table 1
Flux density of Sgr A* at 20 and 6 cm observed with the VLA

| 20 cm S(Jy) | 20 cm Array | 20 cm Ref. | 6 cm S(Jy) | 6 cm Array | 6 cm Ref. | Date |
|---|---|---|---|---|---|---|
| .56(.06)* | | | ... | | | 74Jun01 |
| .60(.1 ) | A | 1 | .92(.05) | A | 3 | 81Mar04 |
| ... | | | .95(.05) | A | 3 | 81Mar05 |
| .90(.1 ) | B | 2 | ... | | | 81Jun |
| ... | | | 1.02(.05) | A | 6 | 82Jan |
| ... | | | .80(.04) | A | 3 | 82Apr25 |
| ... | | | .80(.04) | A | 3 | 82Apr26 |
| ... | | | .80(.04) | A | 3 | 82Apr27 |
| .52(.03) | A | 3 | 1.08(.05) | A | 3 | 83Sep02 |
| .54(.03) | A | 3 | 1.04(.05) | A | 3 | 83Sep09 |
| .54(.03) | A | 3 | 1.13(.06) | A | 3 | 83Sep16 |
| .55(.04) | A,B,C,D | 4 | ... | | | 83Oct |
| ... | | | .74(.08) | B/C | 4 | 84Mar |
| .54(.03) | A | 3 | .95(.05) | A | 3 | 85Jan05 |
| .46(.02) | A | 3 | .94(.05) | A | 3 | 85Jan19 |
| .42(.02) | A | 3 | .94(.05) | A | 3 | 85Jan29 |
| .38(.02) | A | 3 | .79(.04) | A | 3 | 86Apr17 |
| .38(.02) | A | 3 | .67(.03) | A | 3 | 86Apr29 |
| .44(.02) | A | 3 | .88(.04) | A | 3 | 86May29 |
| ... | | | .60(.05) | A | 7 | 87Aug14 |
| .30(.02) | A | 5 | .55(.06) | A | 5 | 87Sep26 |

* The flux density was measured at 1.66 GHz using the Jodrell Bank Interferometer (Davies *et al.* 1976).

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References to VLA observations:

1. Backer (1982)
2. Ekers *et al.* (1983)
3. Backer and Sramek (1987)
4. Goss *et al.* (1987)
5. Ekers, Zhao and Lo (1987)
6. Brown and Johnson (1983)
7. Braun (1987)

Table 2
Flux density of Sgr A* at 11 and 3.7 cm observed with the NRAO Green Bank Interferometer

| S(Jy) 11 cm | S(Jy) 3.7 cm | Date | S(Jy) 11 cm | S(Jy) 3.7 cm | Date |
|---|---|---|---|---|---|
| .600(.005)‡ | .800(.015)‡ | 74Jun01 | .595(.009) | .800(.015) | 77Sep27 |
| ... | .600(.100)† | 75May19 | .611(.009) | .798(.015) | 77Sep28 |
| .417(.009) | ... | 75Oct27 | .569(.009) | .791(.015) | 77Oct20 |
| .427(.009) | .654(.015) | 75Dec02 | 541(.009) | .780(.015) | 77Oct21 |
| .510(.009) | .848(.015) | 76Jan17 | .529(.009) | .576(.015) | 77Dec01 |
| .473(.009) | .668(.015) | 76Feb09 | .687(.009) | .770(.015) | 78Jan02 |
| .465(.009) | .709(.015) | 76Mar21 | .510(.009) | .756(.015) | 78Jan24 |
| .405(.009) | .614(.015) | 76Mar28 | .537(.009) | .605(.015) | 78Feb26 |
| .460(.009) | .842(.015) | 76Apr02 | .502(.009) | .717(.015) | 78Mar31 |
| .444(.009) | .665(.015) | 76Apr06 | .562(.009) | .765(.015) | 78Apr01 |
| .492(.009) | .668(.015) | 76Sep28 | .491(.009) | .583(.015) | 78Apr02 |
| .482(.009) | .604(.015) | 77Feb02 | .532(.009) | .700(.015) | 78Apr03 |
| .453(.009) | .577(.015) | 77Feb03 | .562(.009) | .756(.015) | 78Apr04 |
| .503(.009) | .634(.015) | 77Feb04 | .734(.009)* | .910(.015)* | 81Apr |

All data taken from Brown and Lo (1982) except those marked by *,† and ‡.
*The magnitude of the flux densities are taken from Backer's (1982) spectrum including the estimated errors in the blankets.
†The magnitude of the flux densities are measured by VLBI (Lo *et al.* 1975).
‡Balick and Brown (1974).

Table 3

| $\lambda$ (cm) | $\tau$ (year) | m (%) |
|---|---|---|
| 20 | $\geq$ 5 | 19 |
| 11 | $\geq$ 1.5 | 14 |
| 6 | $\sim$ 0.5 | 17 |
| 3.7 | ? | 14 |

## 3. RESULTS

In Fig. 1 we present the combined results corresponding to 20, 11, 6 and 3.7 cm. We have carried out a statistical analysis of the data following the methods described by Hjellming and Narayan (1986) and estimated the variability timescale, $\tau$, and modulation index, $m$, at each of the wavelengths. The timescale $\tau$ is the $e^{-1}$ width of the intensity auto-correlation function and the modulation index is defined to be $m = \sigma/S_0$, where $S_0$ is the mean flux density at the observed wavelength and $\sigma$ is the standard deviation. The results are summarized in Table 3.

Panel (a) in Fig. 1 shows a long-term secular decrease of the flux density of Sgr A* at 20 cm over the duration of the VLA observations. The timescale is not well-determined since the data do not extend over a sufficiently long period. It is likely that $\tau$ is greater than 5 years but not significantly greater since the flux density varied by nearly a factor of two during the observations. At 11 cm, the flux density of Sgr A* showed a secular increase during the 2.5 years of measurements. We estimate the timescale to be $\geq 1.5$ y. The 6 cm curve may have two timescales, a well-defined short one of about 0.5 y and a less-certain long one of about 5 y. Since the data are taken from individual observations, the sampling is imperfect. We are planning further observations at 6 cm with better sampling. There is no evidence for any slow variation of the flux density at 3.7 cm but there are strong irregular variations from one measurement to the next. We are unable to estimate a timescale at 3.7 cm.

The modulation indices at the four wavelengths, given in Table 3, are large and appear to be independent of wavelength.

## 4. VARIABILITY DUE TO REFRACTIVE INTERSTELLAR SCINTILLATION

Kellermann and Pauliny-Toth (1981) review mechanisms for intrinsic flux density variations in compact radio sources. Their burst model of black hole activity cannot explain the long-term variations in Sgr A*; The small linear size of the source, $2 \times 10^{14}$ cm (Lo 1987), should give a variability timescale of only a few hours. Other slower mechanisms can probably be invoked. However, we concentrate here on the possibility that the variability in Sgr A* may be due to refractive interstellar scintillation (RISS). The apparent FWHM angular size, $\theta$, of Sgr A* varies with wavelength, $\lambda$, as (Davies *et al.* 1974, Lo 1987)

$$\theta \sim 1.2\,\lambda^2 \text{ mas}, \quad \text{with } \lambda \text{ in cm.} \tag{1}$$

The scaling with $\lambda$ is consistent with that expected from scattering and provides compelling evidence that the radiation from Sgr A* is strongly scattered before it reaches the earth. It then follows that the source should display RISS. This is the motivation behind the present investigation.

### 4.1. Variability Timescale

Rickett (1986) gives the following approximate formula for the timescale of RISS,

$$\tau = \frac{L\theta}{1.7v}, \qquad (2)$$

where $\theta$ is the angular size (FWHM) of the scatter-broadened image, $L$ is the distance between the scattering screen and the observer and $v$ is the transverse velocity of the screen with respect to the line-of-sight connecting the source and the observer. The factor of 1.7 is to convert from FWHM to radius at $e^{-1}$. Since $\theta \propto \lambda^2$ for Sgr A*, we expect $\tau \propto \lambda^2$ if the variability is due to RISS. The timescales in Table 3 are consistent with this scaling and can be expressed approximately as

$$\tau \sim 0.013\ \lambda^2\ \text{y}, \quad \text{with } \lambda \text{ in cm}. \qquad (3)$$

The fact that the scaling is consistent with this theory indicates that the variability of Sgr A* could well be due to RISS.

The region around Sgr A* has a high density of turbulent ionized gas and it is reasonable to assume that most of the scattering seen in the source is due to this material. Therefore, we choose $L = 8$ kpc, a reasonable value for the distance to the galactic center. Substituting eqs. (1) and (3) into (2) then leads to an estimate for the velocity, $v \sim 2000$ km s$^{-1}$. This is a very large velocity. Maps of the central region of Sgr A in the 12.8-$\mu$m [Ne II] fine-structure line (Lacy *et al.* 1980, Serabyn and Lacy 1985) and the 76$\alpha$ H I recombination line (Van Gorkom *et al.* 1985, 1988) give a maximum velocity of only $\pm 260$ km s$^{-1}$. A higher velocity of $\pm$ 700 km s$^{-1}$ was found in the gas flow near IRS 16 by Geballe *et al.* (1984, 1987) based on their map of the broad, near-infrared lines of He I and H I. However, even this velocity falls short of the velocity needed to explain the radio variability timescales by more than a factor of two.

One possible resolution of this difficulty is to note that the image of Sgr A* is elongated along a direction almost parallel to the rotation axis of the Galaxy (Lo *et al.* 1985). The measured axial ratio is 0.55. If the velocity vector in the scattering material is in the plane of the Galaxy, then the effective $\theta$ to be used in eq. (2) is approximately half that given in eq. (1). This reduces the velocity estimate to $\sim$ 1000 km s$^{-1}$. The required velocity is still large, but closer to the Geballe *et al.* measurements.

## 4.2. Modulation index

The modulation indices $m$ in Table 3 describe the magnitude of flux density variations in Sgr A* at the four wavelengths. The modulation index expected from RISS depends on the spectrum of density fluctuations in the scattering screen (Goodman and Narayan 1985). For the standard Kolmogorov spectrum, the value of $m$ predicted by the thin-screen scattering theory is significantly less than the fluctuation levels observed in Sgr A* (Table 3). However, Coles *et al.* (1987) and Romani, Narayan and Blandford (1986) have shown that the fluctuations are enhanced when the scattering occurs in an extended medium rather than in a single thin-screen. If the scattering in Sgr A* occurs in a cloud whose extent along the line-of-sight is comparable to its distance from the source, then the geometry will correspond to an extended medium and it may be possible to explain the enhanced variability. An extended cloud will also modify the proportionality constant in eq. (2) and may help reduce the derived velocity of the scattering screen. We are currently looking into this possibility.

## 5. CONCLUSION

The long-term variations in Sgr A* show many characteristics that would suggest an origin in refractive interstellar scintillation. The scattering probably occurs in the vicinity of the galactic center. However, the timescale of the variability leads to an estimate $\sim 1000 - 2000$ km $s^{-1}$ for the velocity of the ionized scattering material and such high velocities have not been observed in this region.

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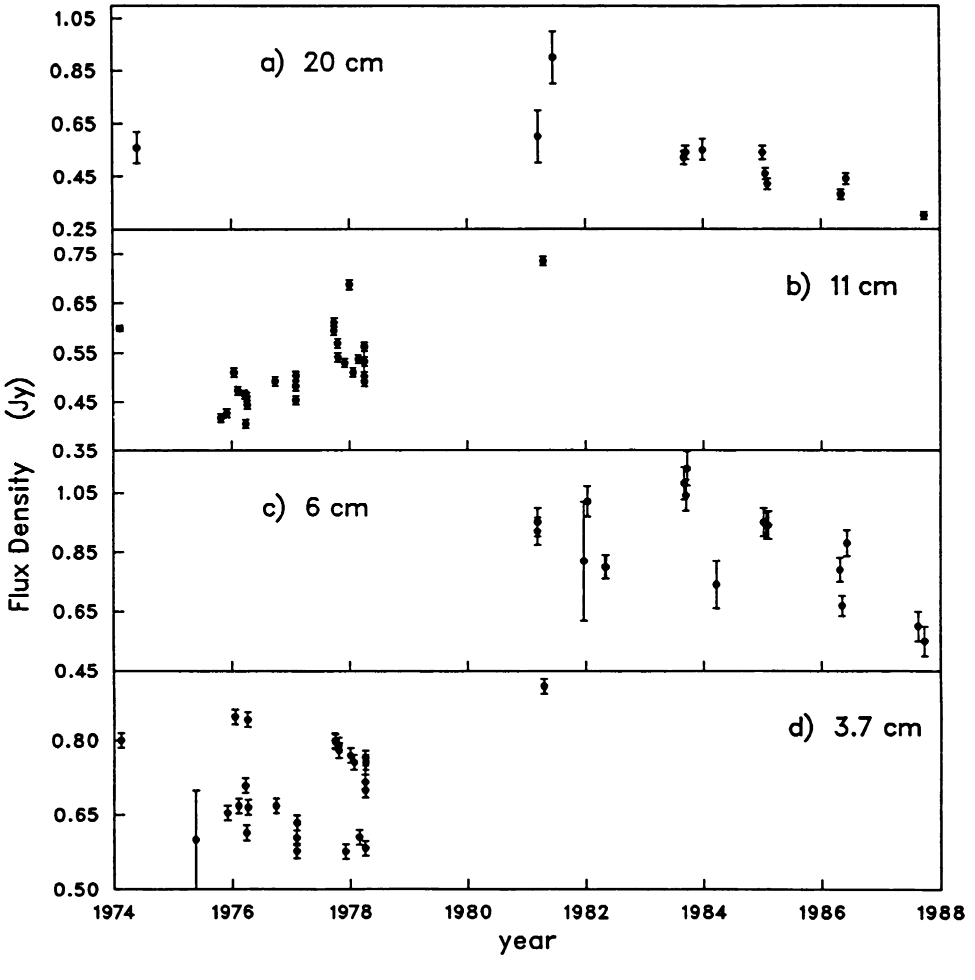


Fig. 1: Long-term flux density variations of Sgr A* at four wavelengths. The 20 cm and 6 cm data (panels a and c) were obtained mostly with the VLA (Table 1). The 11 cm and 3.7 cm data (panels b and d) were measured with the NRAO Green Bank interferometer (Table 2).

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