INTEGRATED POLARIZATION PROPERTIES OF 3C48, 3C138, 3C147, AND 3C286

R. A. PERLEY AND B. J. BUTLER
National Radio Astronomy Observatory, P.O. Box O, Socorro, NM 87801, USA; RPerley@nrao.edu, BBButler@nrao.edu
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ABSTRACT
We present the integrated polarization properties of the four compact radio sources 3C48, 3C138, 3C147, and 3C286, from 1 to 50 GHz, over a 30 yr time frame spanning 1982–2012. Using the polarized emission of Mars, we have determined that the position angle of the linearly polarized emission of 3C286 rises from 33° at 8 GHz to 36° at 45 GHz. There is no evidence for a change in the position angle over time. Using these values, the position angles of the integrated polarized emission from the other three sources are determined as a function of frequency and time. The fractional polarization of 3C286 is found to be slowly rising, at all frequencies, at a rate of ~0.015% yr⁻¹. The fractional polarizations of 3C48, 3C138, and 3C147 are all slowly variable, with the variations correlated with changes in the total flux densities of these sources.

Key words: instrumentation: interferometers – methods: data analysis – methods: observational – techniques: interferometric – techniques: polarimetric

1. INTRODUCTION
Perley & Butler (2013) have proposed an absolute spectral flux density scale valid from 1 to 50 GHz, based on the known absolute emission spectrum from the Wilkinson Microwave Anisotropy Probe observations of the planet Mars (Weiland et al. 2011), and employing accurate flux density ratios derived by the Very Large Array approximately yearly since 1983. They propose that the quasar 3C286, whose flux density has been stable to ~1% over the past 30 yr, be employed as the primary flux density calibrator source for frequencies between 1 through 50 GHz, and provide a polynomial expression for its spectral flux density. In addition, Perley & Butler (2013) provide time-variable polynomial expressions for the spectral flux densities of 3C48, 3C138, and 3C147.

The 19 separate observing sessions utilized by Perley & Butler (2013) provide a database from which the polarization properties of the 14 target sources can be determined. In addition, since the planet Mars was included in this program, its well known polarization characteristics can be utilized to establish the true position angle of polarized emission of the other sources.

In this paper, we briefly describe the polarization calibration procedure, and give results for the integrated polarization properties of the four most compact sources in the program—3C48, 3C138, 3C147, and 3C286.

2. POLARIZATION CALIBRATION
2.1. Observing Methodology and Calibration
The observing methodology and calibration procedures are described in detail in Perley & Butler (2013), and will not be repeated here. The additional calibration steps employed to determine the antenna and source polarizations, and the position angle of linearly polarized flux density are given below.

1. The position angle rotation introduced by the earth’s ionosphere was estimated by utilizing Total Electron Content data from the Crustal Dynamics Data Information System data archive with a model of Earth’s magnetic field. The predicted corresponding phase rotations were applied to the Left Circular Polarization (LCP) data. The corrections are typically a few degrees at 1.5 GHz, and are unimportant above ~5 GHz.

2. The antenna polarizations were measured utilizing the technique of Conway & Kronberg (1969) which utilizes the rotation of the antenna parallactic angle, Ψ, over time. This rotation permits a separation of the antenna from the source polarizations, and provides estimates of each.

3. The plane of linear polarization was based initially by adjusting the phase of the LCP channel so the observed position angle of the polarized flux density from 3C286 was 33° at all frequencies.

Following this calibration procedure, images for all sources in Stokes parameters Q and U were made for each epoch. The polarized images of the optically thin unpolarized source NGC 7027 demonstrate the accuracy of our determinations of the fractional polarization to be typically 0.1%.

Our observing program comprised 14 sources, observed at all VLA frequency bands in the lowest-resolution “D” configuration. The polarization imaging results for the heavily resolved sources 3C123, 3C196, and 3C295 show a complicated polarization pattern, with an integrated fractional polarization typically less than 1%. Because of this, these sources are not useful as polarization calibrators. No linear polarization, to a limit ~0.1%, was found for the planetary nebulae NGC 7027 and NGC 6572, the evolved star MWC349, and the planets Uranus and Neptune. Venus does show detectable polarization from its surface at low frequencies, but the low resolution at these frequencies, and the poor quality of the data, due to Venus’ close proximity to the Sun, do not permit accurate polarimetry.

The sources 3C48, 3C138, 3C147, and 3C286 are all significantly polarized at most frequencies utilized by the VLA. All are very compact, and are thus useful for polarization calibration purposes, providing their integrated polarization properties are at most slowly variable. The planet Mars was sufficiently resolved on 12 observing sessions at our higher frequencies that its polarization can be imaged and utilized to calibrate the position angle for the other sources. The procedure is described in the following section.
3. THE POSITION ANGLE FOR THE POLARIZED FLUX OF 3C286

Most VLA users have adopted the value of 33° for the position angle of the linearly polarized flux density of 3C286 at all frequencies. This value was determined by Bignell & Seaquist (1973) with a quoted error of ±0:9°, and is based on observations at 6.7 GHz with the Algonquin Radio Telescope. Bignell & Seaquist (1973) also give a position angle of 31° ± 1°:3 for 3C286 at 10.7 GHz. We are not aware of any systematic effort to measure the position angle of 3C286 at other frequencies in order to check the common assumption that the position angle is independent of wavelength. Our observations of Mars provide the capability to make this check for the higher frequencies where we are able to resolve the planet’s disk, as the emission of blackbody radiation from a planet such as Mars will show a radially oriented linear polarization which maximizes near the limb of the planet (Heiles & Drake 1963).

For a solid body such as Mars, the thermal radio emission originates from beneath the surface, and upon crossing the surface, is refracted according to Snell’s law

\[ \sin \theta_i = \frac{n_i}{n_t} \sin \theta_t, \]  

where \( \theta \) is the propagation angle with respect to the surface normal, \( n = \sqrt{\epsilon} \) is the index of refraction, \( \epsilon \) is the dielectric constant for the particular medium, and the subscripts \( i \) and \( t \) represent the media for the incident and transmitted radiation. (We assume non-magnetic media, for which \( \mu = 1 \)). Because of the changes in media properties at the planetary surface, from \( n_i > 1 \) to \( n_t \sim 1 \), part of the emerging wave is reflected, and part transmitted. The fraction transmitted depends upon the angle of incidence, the dielectric constant, and the polarization. The transmissivity (defined as the fraction of the incident power which is transmitted across the boundary) is given by (Born & Wolf 1980)

\[ T_\parallel = \frac{\sin 2 \theta_i \sin 2 \theta_t}{\sin^2(\theta_i + \theta_t) \cos^2(\theta_t - \theta_i)} \]  

\[ T_\perp = \frac{\sin 2 \theta_i \sin 2 \theta_t}{\sin^2(\theta_i + \theta_t)} \]  

The parallel linear polarization component lies in the plane defined by the incident and transmitted propagation directions. The perpendicular component is orthogonal to this plane.

Assuming a simple model where Mars is a smooth uniform sphere of radius \( R \), the radiation emitted toward the observer from a location with perpendicular offset \( d \) from the center of the visible disk leaves the planet surface at angle \( \sin \theta = d/R \) to the local planet normal. Defining \( x = d/R \) as the fractional perpendicular offset from the planet center, the transmissivity can be written, using Equations (1)–(3) as

\[ T_\parallel(x) = \frac{4\epsilon \sqrt{1 - x^2} \sqrt{\epsilon - x^2}}{(\epsilon \sqrt{1 - x^2} + \sqrt{\epsilon - x^2})^2} \]  

\[ T_\perp(x) = \frac{4\sqrt{1 - x^2} \sqrt{\epsilon - x^2}}{(\sqrt{1 - x^2} + \sqrt{\epsilon - x^2})^2}. \]  

The parallel component is radially oriented, and the perpendicular component is azimuthally oriented. It can be shown that \( T_\parallel > T_\perp \) for \( 0 < x < 1 \). Further, \( T_\parallel \) rises from the planet center outward, reaches a maximum of unity at the Brewster angle, \( x = \sqrt{\epsilon/(1 + \epsilon)} \), and falls dramatically thereafter, while \( T_\perp \) declines uniformly with offset. Hence, the observed emission will be radially polarized, with the fractional polarization increasing with offset. The fractional degree of polarization

\[ p = \frac{T_\parallel(x) - T_\perp(x)}{T_\parallel(x) + T_\perp(x)} \]  

is a strong function of the planet dielectric constant \( \epsilon \), rising from zero at the planet center to a maximum very near to the planet’s limb (Heiles & Drake 1963). For Mars, with \( \epsilon \sim 2.5 \) (Rudy et al. 1987), the maximum linear polarization would exceed 30%, were the Martian surface smooth.

Finite angular resolution and surface roughness will reduce the observed fractional polarization (Hagfors & Morriello 1966; Alekseev et al. 1968; Golden 1979), but the radial position angle relation will be preserved on large scales, allowing a position angle calibration to be established for observations which adequately resolve the planet’s disk. To illustrate this effect, we show in Figure 1 images of the polarized intensity, and the position angle of the polarized intensity at 43 GHz, taken from our observations on 1999 April 16, when Mars had an angular diameter of 15.6 arcsec. The instrumental resolution is 2.0 arcsec.

Of the 13 observing sessions which included the planet Mars, 12 were taken when Mars had an angular diameter sufficiently large to resolve its polarization in at least one frequency band. For these sessions, we made polarization images of Mars at all frequencies where there were at least three resolution elements across the planet. The lowest frequency at which this could be done for our observations was 5 GHz. A special AIPS task was written to find the mean deviation of the observed position angle around the planet’s disk from the radial direction. This deviation was then added to the assumed value of 33° for 3C286 to determine the correct position angle for that source. The measured position angles for the remaining sources were subsequently corrected using this offset. The observed deviations, and (1σ) error are given in Table 1. The two entries in each of the last three observing sessions reflect the new tuning capabilities of the VLA which were enabled as part of its upgrade (Perley et al. 2009)—these permitted a much wider separation of the two simultaneously observed frequencies. The bottom line in Table 1 gives the weighted mean of the data and the probable error. The corrected values for 3C286 are given in Table 2.

3.1. Polarization Properties for the Four Primary Calibrators

In Table 3 we show the fractional linear polarizations, and the position angles of the polarized intensity from the four compact sources, taken from the observation run of 2010 December. The position angles are referenced to 3C286, which were set to 33° for frequencies between 1 and 8 GHz, and to the angles given in Table 2 for higher frequencies. These same data, in graphical form, are shown in Figure 2, following adjustment for the rotation measure. In this figure, the position angle data for 3C147 at frequencies less than 7 GHz are not shown, as the source is too heavily depolarized to allow a meaningful determination of the position angle.

The position angle of the linearly polarized flux density changes rapidly with wavelength for 3C48 and 3C147. For both, the relationships are well fitted by a \( \lambda/(\text{RM})^2 \) law: \( \chi(\lambda) = (\text{RM})\lambda^2 + \chi_0 \), over part of the frequency range spanned by our
observations. We made a least squares fit to this function for all four sources, with the results given in Table 4. Included in the table are the wavelength ranges over which the RM fits are applicable.

Of interest is any variation in the polarization properties of these sources over time. The recent outburst in 3C138 and the smaller changes in 3C48 and 3C147 (see Perley & Butler 2013) may be expected to result in changes in polarization, as the polarized emission from the emerging component may not align with that from the larger-scale, older emission. Shown in Figure 3 is the temporal variation in the fractional polarization and in the position angles of the four primary calibration sources since 1983.

The figure shows that the fractional polarization of 3C48 has undergone a small but notable rise since this monitoring program began, although there appears to be no effect in the position angle. As expected, there has been a dramatic change in the polarization properties in 3C138, most notably at the higher frequencies, since 2003, when the flare noted by Perley & Butler (2013) began. With the flare intensity now waning, the polarization properties appear to be returning to the relatively stable values noted before 2003. The flux density changes noted by Perley & Butler (2013) for 3C147 are accompanied by small changes in its polarization, particularly at higher frequencies.

Figure 1. Left: a gray-scale image of the linearly polarized intensity from Mars, with a resolution of 2 arcsec, on 1999 April 16. The planet diameter is 15.6 arcsec. Right: a contour plot of the same image, with the apparent position angle of polarized flux density superposed. A small deviation from purely radial is apparent.

Table 1
Offset Angles from 33° of Mars’ Polarized Emission

| Session | 3 cm | 2 cm | 1.3 cm | 1.0 cm | 0.7 cm |
|---------|------|------|--------|--------|--------|
| 1995    | -1.0 ± 1.8 | -0.5 ± 1.0 | -2.9 ± 1.0 | -4.4 ± 0.5 |
| 2000    | -0.7 ± 7.0 | -3.1 ± 3.2 | -2.2 ± 4.3 |
| 2001    | 0.4 ± 4.0  | -3.7 ± 2.5 |
| 2004    | 2.3 ± 3.5  |
| 2006    | -0.3 ± 2.4 | -3.2 ± 1.1 | -0.5 ± 1.2 |
| 2007    | 2.0 ± 8.8  | 0.4 ± 3.7  |
| 2008    | 0.5 ± 3.8  |
| 2010    | -0.6 ± 4.3 | -1.5 ± 1.2 | -2.6 ± 1.1 | -4.4 ± 0.5 |
|         | 0.7 ± 4.0  | -1.3 ± 1.6 | 1.9 ± 1.4 |
| 2011    | -1.8 ± 3.2 | -1.6 ± 2.2 | 1.7 ± 2.0 | 0.5 ± 3.6 |
|         | -1.9 ± 3.9 | 3.9 ± 1.3  |
| 2012    | 0.6 ± 3.9  | -3.5 ± 1.3 | 0.4 ± 0.8 | -4.1 ± 1.0 | -2.6 ± 0.9 |
|         | 0.5 ± 2.9  | -1.2 ± 1.5 | -2.3 ± 0.8 | -4.5 ± 0.8 | -3.3 ± 0.6 |
| Wgt. Mean | -0.3 ± 0.9 | -1.6 ± 0.3 | -1.91 ± 0.12 | -2.50 ± 0.33 | -2.77 ± 0.10 |

Notes. The last line gives the weighted mean of the tabular entries for each wavelength band. The listed error is the weighted (1σ) error.

Table 2
The Measured Polarization Position Angle for 3C286

| P.A.  | 5 GHz | 15 GHz | 23 GHz | 33 GHz | 45 GHz |
|-------|-------|--------|--------|--------|--------|
| 3C286 | 33 ± 1 | 34.5 ± 0.5 | 35 ± 0.2 | 35.5 ± 0.4 | 35.8 ± 0.1 |
The fractional polarization of 3C286 appears to be slowly and steadily rising over the period. A simple linear fit to the data provides the values shown in Table 5, giving the fractional polarization in percent for epoch 2000.0, and its change in % century$^{-1}$.

Examination of Figure 3 shows evidence of sudden, short-term drops in fractional polarization of typically $\sim0.2\%$, most notably at higher frequencies. Similar and uncorrelated changes in the position angle are also seen at all bands. Except at the highest frequency band, these changes are far above the
Figure 3. The percentage polarization and the polarization position angle for 3C48 (upper left), 3C138 (upper right), 3C147 (lower left), and 3C286 (lower right, fractional polarization only). The error bars are computed from the rms thermal noise in the Q and U images, and do not include possible errors in calibration.

### Table 4
RM Values for the Four Sources

| Source | Wavelength Range (cm) | RM (rad m⁻²) | Z₀ (deg) |
|--------|----------------------|--------------|---------|
| 3C48   | 1–18                 | -68          | 122     |
| 3C138  | 2–22                 | 0            | -10     |
| 3C147  | 1–3                  | -1467        | 88      |
| 3C286  | 3–> 30               | 0            | 33      |

### Table 5
Change in Fractional Polarization of 3C286

| Frequency (GHz) | P(2000) (%) | Slope (% century⁻¹) |
|-----------------|-------------|---------------------|
| 1.465           | 9.47 ± 0.02 | 0.7 ± 0.2           |
| 4.885           | 11.15 ± 0.03| 1.6 ± 0.2           |
| 8.435           | 11.69 ± 0.02| 1.5 ± 0.3           |
| 14.965          | 11.94 ± 0.05| 1.5 ± 0.6           |
| 22.485          | 12.22 ± 0.06| 1.5 ± 0.6           |
| 43.340          | 13.1 ± 0.1  | -1.6 ± 1.7          |

uncertainties in the measurements which can be expected from thermal noise. We believe it is quite unlikely that these changes are real, as they are not correlated amongst adjacent frequency bands, as we would expect for broad-band synchrotron radiation. They are more likely due to errors in the polarization calibration. We identify four possible origins:

1. Uncorrected estimates in ionospheric Faraday rotation. These will rotate the plane of polarization of the incoming radiation and will result in an incorrect derived position angle. This effect can only significantly affect the 1465 MHz observations, and is likely responsible for the exaggerated offsets in the position angles seen for 3C48 and 3C138 in Figure 3 at 1465 MHz.

2. Unmonitored and uncorrected changes in the instrumental phase difference between the two polarizations. For the VLA, such changes correspond to a time-variable rotation of the source’s plane of polarization. Observations of strongly polarized sources at high frequencies (to eliminate Faraday rotation effects) show that changes of a few degrees have occurred on timescales of tens of minutes. The parallel-hand phase calibration process described in Perley & Butler (2013) cannot correct for any time-variable phase changes between the two polarizations. Such changes will affect the calibration of the antenna polarizations, and hence
the measures of source polarization, although we expect the magnitude of this effect to be much smaller than the size of the unexplained drops in fractional polarization.

3. An uncorrected time delay between the two polarization channels. Such a delay will decrease the observed polarized flux by a common factor for all sources observed in that session. Prior to the installation of the new correlator, all observations were taken in a “continuum” mode, which prevents post-observing delay calibration. This was clearly the case for one of our observations—at 1465 MHz for the 2007 observations, where the fractional polarization was reduced by 4.5% for all sources. However, none of the other significant drops in fractional polarization can be ascribed to this, as they are not correlated between sources.

4. Ignoring higher-order terms in the polarization calibration. The polarization calibration utilized only the first-order terms, which describe the leakage of Stokes $I$ into the RL and LR visibility products through the antenna cross polarization. Ignored are the coupling of Stokes $V$ into RL and LR, and a second-order product that cross-couples the source linear polarization. However, both of these terms are important only at a level much less than $\sim 0.1\%$, and seem unlikely to be the cause of the observed polarization drops.

We find it difficult to explain the short-term, single-frequency drops in polarization fraction shown in Figure 3 through any combination of these mechanisms, and conclude that the current limiting accuracy in VLA polarimetry is typically $\sim 0.3\%$ and $\sim 5^\circ$.

4. DISCUSSION

All four sources have been extensively observed with the Very Long Baseline Array (VLBA), MERLIN, and European VLBI Network (EVN). Here we briefly compare the polarimetric results from these instruments against our own.

4.1. 3C48

The source was the subject of an extensive study by An et al. (2010), utilizing the VLBA, MERLIN, and the EVN. Their paper shows that the emission from 3C48 on milliarcsecond scales is quite complicated, with a short and twisted jet-like structure blending into an extended region located to the NE of the quasar core. Our global rotation measure value of $-68$ rad m$^{-2}$ is in good agreement with the “spot” values from their component “C” of $-68$ to $-95$ rad m$^{-2}$. The MERLIN polarimetric image at 1.65 GHz shows the weak polarized emission aligned nearly vertically, in good agreement with our integrated value of $-5^\circ$ at 1.64 GHz. The heavily resolved VLBA images shown in their Figure 6 at 4.78 and 8.31 GHz are difficult to compare to our integrated values, but the polarized position angles shown are close to our integrated values. High resolution VLA images taken at 26 GHz with 70 mas resolution show the majority of the polarized emission coming from bright northern component labeled “C” in An et al. (2010), with the more compact structures labeled by them as “B,” “B2,” and “B3.”

4.2. 3C138

The small-scale structure is shown in Cotton et al. (1997a) to comprise a relative weak unresolved nuclear core, a strong and well-resolved jet-like structure extending $\sim 400$ mas to the NE, and a very weak counter-jet 250 mas to the SW. The NE jet is highly and uniformly polarized, and accounts for nearly all the total polarized emission seen in our integrated measures. Their Figure 4 shows the weaker, trailing parts of the NE jet to have a linearly polarized emission at P.A. $\sim -25^\circ$, while the much brighter head of the jet to have its polarized emission at an angle near 0. The mean of the two components is near our integrated measure of $\sim 10^\circ$. Our data show the position angle to decrease by about 15$^\circ$ as the frequency rises—this is probably due to a spectral index effect whereby the head of the NE jet becomes more prominent compared to the steeper spectrum trailing areas. The decline in integrated polarization, and decrease in the resulting position angle, seen since 2002 at the higher frequencies are likely due to an emerging new component along P.A. near $-30$ (as shown in Figure 6 in Cotton et al. 1997a) with polarization along this angle.

4.3. 3C147

VLBA polarimetric imaging at 5 and 8 GHz for 3C147 has been presented by Rossetti et al. (2009). At milliarcsecond resolution, the source comprises a compact core and apparently rapidly expanding jet, extending only $\sim 10$ mas to the SW. Beyond this, a very diffuse and well-resolved lobe extends to the SW to a maximum extent of $\sim 180$ mas. High resolution VLA observations at $\sim 70$ mas resolution show another, more extended and detached elongated lobe extending northward $\sim 700$ mas. 3C147 has an extremely high RM of $-1467$ rad m$^{-2}$, in good agreement with the value reported by Rossetti et al. (2009) for their component B, located at the end of the inner, flaring jet. High resolution VLA polarimetric imaging at 25 GHz with 70 mas resolution shows that the nucleus and inner jet regions dominate the total polarized flux density. The true integrated position angle of $88^\circ$ from our integrated measures agrees well with the intrinsic angle for the B-field of the flaring jet shown by Rossetti et al. (2009) in their Figure 7.

4.4. 3C286

The quasar 3C286 was selected by Perley & Butler (2013) as the primary non-variable flux density standard from 1 to 50 GHz, based on the stability of its total intensity over a period exceeding 30 yr. This current study shows that 3C286 also serves as an equally useful and stable reference source for polarimetry. Although we detect a very small secular increase in its polarized flux density, the change appears to be steady, permitting easy calculation of the expected polarized flux density at any epoch.

High resolution polarimetry of this source is shown by Jiang et al. (1996) and Cotton et al. (1997b). The latter paper sketches the overall structure, comprising a central core, a compact lobe about 1 arcsec east, and an elongated western lobe, extending $\sim 2.5$ arcsec to the SW. The central core region contains a highly polarized extension of length $\sim 80$ mas, in P.A. 45$^\circ$—i.e., pointing toward the SW extension. Both the total and polarized emission from this source are unusual. There is no clearly defined inverted spectrum core, suggesting either a dearth of recent activity, or a geometry whereby the core emission is beamed away from our direction. The polarized emission is almost entirely along the jet, with remarkably uniform fractional polarization.

3C286 has recently been proposed by Agudo et al. (2012) as a polarization calibration source for millimeter-wavelength observations. Using IRAM observations, they give a polarization fraction of 13.5% $\pm 0.3\%$ and an intrinsic position angle of 37.4$\pm 0.8$ at $\lambda = 3$ mm. Agudo et al. (2012) also provide values at $\lambda = 1$ mm of 14.5% and 33:5—however,
these have much larger error estimates, and are not inconsistent with our results. Recent CARMA observations (C. Hull 2013, private communication) have shown the polarization position angle to be $41^\circ \pm 0.5$ at $\lambda = 1$ mm. Both of these recent results are in excellent agreement with our observed trend of increasing position angle with increasing frequency.

5. SUMMARY

We have determined that the position angle of linearly polarized emission from 3C286 rises from $33^\circ$ at frequencies below 10 GHz to $36^\circ$ at 43 GHz. Recent millimeter-wave observations by IRAM and CARMA indicate that this increase in position angle with frequency continues up to 300 GHz. Changes in this position angle over time are less than $\sim 2^\circ$ over the past 20 yr at frequencies less than 50 GHz. The fractional linear polarization of 3C286 is steadily increasing at all frequencies at a rate of about 0.015% yr$^{-1}$.

The polarization characteristics of 3C48 and 3C147 are fairly stable, but small changes, likely related to the small variations in total intensity noted by Perley & Butler (2013) are visible, most notably in 3C147 above 20 GHz. The polarization position angles for both sources are stable to $\sim 5^\circ$ over the 30 yr duration of this investigation. The polarization position angles for these two objects for frequencies at which their fractional polarization exceed 1% are well fitted with a simple $\lambda^2$ law over most of the observed frequency range.

The strongly polarized source 3C138 has undergone a notable flare, beginning in 2003, which nearly doubled its total intensity by 2010, and has been rapidly declining since. The polarization properties also changed dramatically during this period, and appear to be returning to the pre-flare levels.

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