SEVEN-YEAR WILKINSON MICROWAVE ANISOTROPY PROBE (WMAP) OBSERVATIONS: PLANETS AND CELESTIAL CALIBRATION SOURCES

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ABSTRACT

We present WMAP seven-year observations of bright sources which are often used as calibrators at microwave frequencies. Ten objects are studied in five frequency bands (23–94 GHz): the outer planets (Mars, Jupiter, Saturn, Uranus, and Neptune) and five fixed celestial sources (Cas A, Tau A, Cyg A, 3C274, and 3C58). The seven-year analysis of Jupiter provides temperatures which are within 1σ of the previously published WMAP five-year values, with slightly tighter constraints on variability with orbital phase (0.2% ± 0.4%), and limits (but no detections) on linear polarization. Observed temperatures for both Mars and Saturn vary significantly with viewing geometry. Scaling factors are provided which, when multiplied by the Wright Mars thermal model predictions at 350 GHz band. Intriguingly, the spectrum of Uranus appears to show a dip at ∼30 GHz of unidentified origin, although 3%–4% in the 41, 61, and 94 GHz bands; the smallest uncertainty for Neptune is 8% for the 94 GHz band. Intriguingly, the spectrum of Uranus appears to show a dip at ∼30 GHz of unidentified origin, although the feature is not of high statistical significance. Flux densities for the five selected fixed celestial sources are derived from the seven-year WMAP sky maps and are tabulated for Stokes I, Q, and U, along with polarization fraction and position angle. Fractional uncertainties for the Stokes I fluxes are typically 1% to 3%. Source variability over the seven-year baseline is also estimated. Significant secular decrease is seen for Cas A and Tau A: our results are consistent with a frequency-independent decrease of about 0.53% per year for Cas A and 0.22% per year for Tau A. We present WMAP polarization data with uncertainties of a few percent for Tau A. Where appropriate, WMAP results are compared against previous findings in the literature. With an absolute calibration uncertainty of 0.2%, WMAP data are a valuable asset for calibration work.

Key words: galaxies: individual (Cygnaus A, 3C274) – ISM: supernova remnants – planets and satellites: general – radio continuum: general – space vehicles: instruments

1. INTRODUCTION

The primary goal of the Wilkinson Microwave Anisotropy Probe (WMAP) mission (Bennett et al. 2003b) is to study the cosmic microwave background (CMB) anisotropy, an undertaking that requires detailed knowledge of the instrumental angular response and noise, low systematic errors, and absolute calibration at sub-percent levels. These attributes make WMAP data of natural interest for ancillary studies of sky-based calibration objects. This paper focuses on WMAP observations of selected planets and fixed celestial objects which have been commonly used as calibrators in the microwave, either by ground- or space-based instruments. We provide fundamental measurements for these objects which will be of use not only for calibration purposes, but also other studies, such as planetary radiative transfer.

A brief discussion of WMAP planetary radiometric data was made by Hill et al. (2009), with an earlier discussion of Jupiter temperatures by Page et al. (2003b). We extend these presentations to include WMAP observations of Mars, Jupiter, Saturn, Uranus, and Neptune over a seven-year interval (2001–2008), in five microwave passbands ranging from ∼23 to 94 GHz. We also select five bright celestial sources for more detailed study: Cas A, Cyg A, Tau A, 3C58, and 3C274. The WMAP project routinely compiles and distributes a point-source catalog, which tabulates mean flux values in those same five passbands for bright sources off the Galactic plane (Wright et al. 2009; Hinshaw et al. 2007; Bennett et al. 2003a). However,
four of the five objects discussed here (Cas A, Tau A, Cyg A, 3C 58) have low Galactic latitudes and are not included in the catalog. An earlier analysis of three-year WMAP Tau A observations by Page et al. (2007) included both intensity and linear polarization measurements.

This paper is one of a suite that details the analysis of WMAP seven-year data. An overview and description of data processing methods is provided by Jarosik et al. (2011). Gold et al. (2011) discuss Galactic foregrounds and techniques for removing them; an updated point-source catalog is included. Analysis of CMB power spectra, best-fit models, and cosmological interpretations are presented by Larson et al. (2011) and Komatsu et al. (2011). Bennett et al. (2011) assess potential CMB “anomalies” relative to the best-fit six parameter ΛCDM model.

We organize this paper as follows: a short discussion of the WMAP instrument, plus data strengths and limitations for calibration source work, is provided in Section 2. The paper then divides into two major sections: analysis and results for planets (Section 3), and then Section 4 discusses analysis methods and results for the five bright celestial sources. A closing summary and conclusions follow in Section 5.

2. WMAP OVERVIEW

Since its arrival at the Earth–Sun L2 point in 2001 August, WMAP has produced a well-calibrated, multi-wavelength microwave survey of the entire sky with high-sampling redundancy. Detailed descriptions of the mission profile and hardware can be found in Bennett et al. (2003b), Jarosik et al. (2003a), and Page et al. (2003b). To assist with clarifying the terminology and analysis methods presented in this paper, we describe the key features of the mission.

WMAP observes the sky differentially: signal from the sky is simultaneously sampled in two different directions ∼ 140° apart and guided by 10 feed horn pairs into 10 receivers, referred to as differencing assemblies (DAs). The receivers cover five frequency bands (K, Ka, Q, V, and W) with approximate center frequencies of ∼23, 33, 41, 61, and 94 GHz, respectively. There is one DA each for K and Ka bands (K1, Ka1), two DAs each for Q and V bands (Q1, Q2, V1, V2) and four DAs (W1, W2, W3, W4) for W band. The frequency passbands are broad (∼ 20% fractional bandwidth), so that the exact frequency associated with an observation depends on the source spectrum. An orthomode transducer at the throat of each feed separates the sky signal into two orthogonal polarizations, allowing for reconstruction of both intensity and linear polarization signals. Angular resolution is moderate, ranging from roughly 0.2 FWHM in the W band to ∼0.9 FWHM in K band.

As a survey mission, WMAP is not commanded to point at specific targets, but executes a pole-to-pole sky-scanning strategy whose position on the ecliptic advances ∼1° each day. To facilitate high redundancy in sky coverage, the spacecraft rotates about a spin axis, which also precesses. These combined motions produce a ∼45° wide scan swath which looks like a “belt” projected onto the sky, passing through the ecliptic poles. The scan swath returns to its original starting position on the ecliptic every year, after completing a full-sky survey with multiple observations per sky pixel.

A primary strength of WMAP data is the calibration accuracy, with an absolute calibration error of 0.2% (Jarosik et al. 2011). The absolute calibration is tied to knowledge of the CMB monopole and the spacecraft orbital velocity, and thus is independent of any reliance on previously established measurements of the sources under study. When coupled with WMAP’s temporal and spectral coverage, the accurate flux measurements can provide a useful measure of intrinsic or geometrically induced source variability.

There are some limiting factors, however. Temporal coverage of an object is constrained by the sky-scanning method. For a fixed source on the ecliptic, the WMAP scan strategy provides for two ∼45 day windows a year in which to observe that source. These “observing seasons” are spaced roughly six months apart. While this geometry is modified somewhat for moving objects, only Mars is near enough that the orbital motion can extend a single viewing window from 45 days to as much as 60 to 90 days. Since WMAP does not dwell on an object, but simply scans as it passes through the viewing swath, the number of observations for an individual object is also limited, which affects the signal-to-noise. Finally, WMAP’s moderate spatial resolution, which allows us to characterize the planets as calibrators, also places detailed knowledge of structures such as Saturn’s rings beyond instrument capabilities.

3. PLANETS

There are five planets with sufficient signal-to-noise for analysis. Listed in order of decreasing signal-to-noise, these are Jupiter, Saturn, Mars, Uranus, and Neptune. Since WMAP points away from the Sun, Earth, and Moon in its L2 orbit, it cannot observe Mercury or Venus.

3.1. Data Processing and Analysis Methods

Planets are excluded from the standard map-based products used for WMAP studies of the CMB and Galactic foregrounds. Observations of the planets must be extracted from the calibrated time-ordered data (TOD), and then undergo quality assessment and background removal before they can be analyzed. The extraction process gathers all observations from the TOD taken within several degrees of each planet and associates ancillary information such as position in the focal plane, attitude, planet-viewing aspect, and data quality flags with each observation. Observations whose sky positions lie within 7° radius of other planets or which are of suspect quality are immediately rejected. In addition, observations are excluded from use if either beam of a DA feed-horn pair samples sky coordinates that fall within the boundaries of a spatial processing mask (Jarosik et al. 2007). The purpose of this “Galactic masking” is to mitigate background removal error by excluding observations located near strong-signal, high-gradient regions of the Galaxy. For those observations which survive these quality control steps, Galactic and CMB background signals are subtracted. The background signal subtracted from each observation is computed from the DA-appropriate seven-year mean map (from which planetary data were excluded), using the value from the ∼6’ wide pixel which is closest in spatial coordinates to those of the time-ordered observation. Table 1 lists the beginning and ending dates of the observing seasons for the five planets, i.e., when they are directly in the WMAP viewing swath. The “sky proximity” column in the table indicate probable reasons for an unusually high rejection of observations within a season.

As noted in Page et al. (2003b), planets are “point sources” for WMAP and thus the brightness temperature of a planet $T_p$ can be computed via the relation

$$T_p \Omega_p = T^m \Omega_B,$$

where $T^m$ is the peak response observed by WMAP, $\Omega_B$ is the main-beam solid angle, and $\Omega_p$ is the solid angle subtended by
Table 1

| Planet | Season | Begin | End | SP |
|--------|--------|-------|-----|----|
| Jupiter | 1 | 2001 Oct 8 | 2001 Nov 22 | |
| 2 | 2002 Feb 11 | 2002 Mar 27 | G |
| 3 | 2002 Nov 10 | 2002 Dec 24 | |
| 4 | 2003 Mar 15 | 2003 Apr 29 | G |
| 5 | 2003 Dec 11 | 2004 Jan 23 | |
| 6 | 2004 Apr 15 | 2004 May 30 | |
| 7 | 2005 Jan 9 | 2005 Feb 21 | |
| 8 | 2005 May 16 | 2005 Jul 1 | |
| 9 | 2006 Feb 7 | 2006 Mar 24 | |
| 10 | 2006 Jun 16 | 2006 Aug 2 | |
| 11 | 2007 Mar 10 | 2007 Apr 24 | |
| 12 | 2007 Jul 19 | 2007 Sep 3 | |
| 13 | 2008 Apr 11 | 2008 May 27 | |
| Saturn | 1 | 2001 Sep 7 | 2001 Oct 22 | |
| 2 | 2001 Jan 14 | 2002 Feb 26 | |
| 3 | 2002 Sep 22 | 2002 Nov 5 | |
| 4 | 2003 Jan 28 | 2003 Mar 13 | G |
| 5 | 2003 Oct 7 | 2003 Nov 20 | G |
| 6 | 2004 Feb 12 | 2004 Mar 26 | G |
| 7 | 2004 Oct 20 | 2004 Dec 3 | |
| 8 | 2005 Feb 25 | 2005 Apr 10 | |
| 9 | 2005 Nov 4 | 2005 Dec 17 | |
| 10 | 2006 Mar 11 | 2006 Apr 24 | |
| 11 | 2006 Nov 18 | 2006 Dec 31 | |
| 12 | 2007 Mar 25 | 2007 May 9 | |
| 13 | 2007 Dec 1 | 2008 Jan 13 | |
| 14 | 2008 Apr 7 | 2008 May 22 | |
| Mars | 1 | 2001 Aug 10 | 2001 Oct 14 | |
| 2 | 2001 Sep 19 | 2003 Jul 17 | U, N |
| 3 | 2003 Oct 10 | 2003 Dec 30 | U |
| 4 | 2005 Jul 13 | 2005 Oct 1 | |
| 5 | 2005 Dec 16 | 2006 Feb 19 | |
| 6 | 2007 Sep 18 | 2007 Nov 20 | |
| 7 | 2008 Jan 30 | 2008 Mar 30 | |
| Uranus | 1 | 2001 Sep 30 | 2001 Nov 13 | |
| 2 | 2002 May 20 | 2002 Jul 5 | |
| 3 | 2002 Oct 4 | 2002 Nov 17 | |
| 4 | 2003 May 25 | 2003 Jul 9 | M |
| 5 | 2003 Oct 8 | 2003 Nov 21 | M |
| 6 | 2004 May 28 | 2004 Jul 13 | |
| 7 | 2004 Oct 12 | 2004 Nov 24 | |
| 8 | 2005 Jun 2 | 2005 Jul 17 | |
| 9 | 2005 Oct 16 | 2005 Nov 28 | |
| 10 | 2006 Jun 6 | 2006 Jul 22 | |
| 11 | 2006 Oct 20 | 2006 Dec 3 | |
| 12 | 2007 Jun 10 | 2007 Jul 26 | |
| 13 | 2007 Oct 24 | 2007 Dec 7 | |
| 14 | 2008 Jun 14 | 2008 Jul 29 | |
| Neptune | 1 | 2001 Sep 15 | 2001 Oct 29 | |
| 2 | 2002 May 2 | 2002 Jun 16 | |
| 3 | 2002 Sep 17 | 2003 Jan 19 | M |
| 4 | 2003 May 4 | 2003 Jun 3 | |
| 5 | 2003 Sep 20 | 2003 Nov 3 | |
| 6 | 2004 May 6 | 2004 Jun 21 | |
| 7 | 2004 Sep 21 | 2004 Nov 4 | |
| 8 | 2005 May 8 | 2005 Jun 23 | |
| 9 | 2005 Sep 23 | 2005 Nov 7 | |
| 10 | 2006 May 11 | 2006 Jun 26 | |
| 11 | 2006 Sep 26 | 2006 Nov 9 | |
| 12 | 2007 May 14 | 2007 Jun 28 | |
| 13 | 2007 Sep 28 | 2007 Nov 11 | |
| 14 | 2008 May 15 | 2008 Jun 30 | |

Notes.

* An observing season is defined as a contiguous time interval during which an object is in the WMAP viewing swath.

* sky coordinate proximity to any of the following: Galactic plane (G); Mars (M); Uranus (U), Neptune (N).

Table 2

| Planet | $R_{eq}$ (km) | $R_{pole}$ (km) | $\Omega_{ref}$ (sr) |
|--------|---------------|-----------------|---------------------|
| Mars   | 3396          | 3376            | $7.153 \times 10^{-10}$ |
| Jupiter| 71492         | 68854           | $2.481 \times 10^{-8}$ |
| Saturn | 60268         | 54364           | $5.096 \times 10^{-9}$ |
| Uranus | 25559         | 24973           | $2.482 \times 10^{-10}$ |
| Neptune| 24764         | 24341           | $1.006 \times 10^{-10}$ |

Notes.

* From Seidelmann et al. (2007).

* Solid angle computed at fiducial distances of 1.5, 5.2, 9.5, 19, and 29 AU, respectively. See Section 3.1 for further discussion.
seven years of Jupiter observations. After the processing steps described above, radial response profiles are produced for each planet, per DA, per season, by assigning observations to 0.25 arcmin bins increasing in angular distance from the planet’s center. Each bin is assigned a mean value and an error based on instrument noise appropriate to the number of observations within the bin. The known radial beam response, based on seven-year Jupiter data, is used as a fitting template to the seasonal radial profile for each DA. The fit returns $T_m$ for the planet. The brightness temperature is then derived from $T_m$, the main-beam solid angle (Jarosik et al. 2011) and the reference solid angle for the planet as per the above equations. Errors include the formal error in the template coefficient and the propagated error in the beam solid angle. Figure 1 illustrates sample W1 radial profiles for a single observing season for each of the planets. The beam template is overplotted in red. As well as illustrating the technique, the figure is also a useful comparator of signal quality for each planet at the W band. Beam dilution increases with decreasing WMAP frequency: $\Omega_B$ is roughly 24.6, 14.4, 8.98, 4.20, and $2.10 \times 10^{-5}$ sr for the K–W bands, respectively (Jarosik et al. 2011).

Tabulated brightness temperatures are appropriate for the Rayleigh–Jeans (RJ) approximation. Brightness temperatures provided in the Tables do not include the CMB contribution blocked by the planet but included in the background. As noted in the Tables, absolute brightness temperature is obtained by adding 2.2, 2.0, 1.9, 1.5, and 1.1 K in bands K, Ka, Q, V, and W, respectively (Page et al. 2003a), since in the RJ approximation the CMB temperatures are frequency dependent. WMAP data points shown in comparison to measurements in the literature are converted to absolute brightness.

3.2. Jupiter

Jupiter is a bright, accessible source whose whole-disk observations have long been used for calibration in the infrared through radio. Hill et al. (2009) recommend the use of WMAP radiometry of Jupiter as the preferred method of transferring the WMAP dipole calibration to another microwave instrument. For some instruments, Jupiter is unfortunately too bright, hence the interest in the use of fainter sources, and a set of observations which tie several common sources together on the same calibration scale. We continue to recommend Jupiter as the primary comparison calibrator, however.

Seven-year mean brightness temperatures for Jupiter, computed as described in Section 3.1, are presented in Table 3. The seven-year values differ from those of the five-year analysis of Hill et al. (2009) by 1σ or less. The largest changes, which hover near 1σ, are for the K band and some of the W-band DAs. A detailed explanation of these changes is given in Jarosik et al. (2011). Briefly, the change in K-band results from improved background subtraction, and the W-band changes are driven by small revisions to the beam solid angles, based on modeling. The seven-year temperatures for the W band show a decreased scatter between the individual DAs compared to five-year, implying an improved calibration. The Jupiter temperature uncertainties listed in Table 3 are derived from the quadrature sum of the solid angle error and absolute calibration error of 0.2% (Jarosik et al. 2011), as they were in the five-year analysis.

Thermal emission from Jupiter’s atmosphere is the primary signal source at wavelengths spanned by WMAP. As such, the observations are helpful for providing constraints on atmospheric models for Jupiter, which in turn could be used for calibration purposes. However, as noted by e.g., Gibson et al. (2005), there is a fine point to consider: small contributions to
The observed intensity from a synchrotron component up to about 40 GHz is expected. This non-thermal “decimetric emission” arises from charged particles trapped close to Jupiter by its strong magnetic field, and dominates the spectrum at frequencies less than about 3 GHz. Estimates in the literature place the synchrotron contribution at 23 GHz near 1% of the total intensity (de Pater & Dunn 2003; Gibson et al. 2005), with a roughly $\nu^{-2.4}$ frequency dependence (Klein & Gulkis 1978). However, the synchrotron emission is known to be variable on a wide range of timescales (Santos-Costa et al. 2009; de Pater & Dunn 2003; Miyoshi et al. 2000), and accurate removal is difficult. The $T/T_{\text{obs}}$ is a region in which background subtraction is subject to greater error because of higher temperature gradients across the pixels in the map used for background removal. If one ignores these three entries, then an upper limit of 0.2% ± 0.4% is more appropriate. We also searched for indications that the K band might be more intrinsically variable than the W band, because of the small synchrotron contribution. There is no indication of such a frequency dependence in the data, but the upper envelope here is about 0.5%.

Using the WMAP five-year data, Hill et al. (2009) quote an upper limit of 0.3% ± 0.5% based on the largest deviation and scatter seen in the first 10 observing seasons, which occurred in season four. A careful examination of the entries in Table 4 with the largest deviations and/or scatter (observing seasons 4, 11, 12) shows that these particular instances have more to do with template fitting and background subtraction quality than with intrinsic source variability. The two seasons with high scatter (4, 12) are those in which the number of available observations for fitting has been significantly reduced because of foreground masking ("% masked" in the Table), which increases the statistical error in the temperature determination. Season 11, with the highest $\Delta T/T$, is one in which Jupiter is nearly aligned with the Galactic center, but outside the processing mask. This is a region in which background subtraction is subject to greater error because of higher temperature gradients across the pixels in the map used for background removal. If one ignores these three entries, then an upper limit of 0.2% ± 0.4% is more appropriate. We also searched for indications that the K band might be more intrinsically variable than the W band, because of the small synchrotron contribution. There is no indication of such a frequency dependence in the data, but the upper envelope here is about 0.5%.

The WMAP Jupiter observations were analyzed to determine if any linear polarization signal could be detected. A special version of the beam mapping software was run for Jupiter, in which the angle between the polarization axis of each radiometer and the planet’s magnetic dipole was computed for each observation. For each differencing assembly, all observations within a tight radius of beam center were accumulated, corrected to peak beam response, background subtracted, loss imbalance corrected, separated by radiometer, and then used to solve for Stokes parameters $I, Q, U$, and their errors. For a more complete description of the relevant equations, see Hinshaw et al. (2003) and Jarosik et al. (2007). Normalized Stokes parameters $Q/I$ and $U/I$ are reported in Table 5, along with their propagated errors and estimated linear polarization fraction, $p_{\text{lin}} = \sqrt{(Q/I)^2 + (U/I)^2}$. No attempt has been made to correct for noise bias in either

Table 3

| DA/Band | $\nu_{\text{J}}^b$ | $\lambda$ | $T$ | $\sigma(T)^2$ |
|---------|-------------------|---------|-----|---------------|
|         | (GHz)             | (mm)   | (K) |               |
| Per DA  |                   |         |     |               |
| K1      | 22.85             | 13.1    | 136.2 | 0.85         |
| Ka1     | 33.11             | 9.1     | 147.2 | 0.77         |
| Q1      | 40.92             | 7.3     | 154.4 | 0.91         |
| Q2      | 40.71             | 7.4     | 155.2 | 0.87         |
| V1      | 60.41             | 5.0     | 165.0 | 0.78         |
| V2      | 61.28             | 4.9     | 166.1 | 0.74         |
| W1      | 93.25             | 3.2     | 173.0 | 0.84         |
| W2      | 93.73             | 3.2     | 173.3 | 0.91         |
| W3      | 93.72             | 3.2     | 173.7 | 0.94         |
| W4      | 93.57             | 3.2     | 173.9 | 0.92         |
| Per band|                   |         |     |               |
| K       | 22.85             | 13.1    | 136.2 | 0.85         |
| Ka      | 33.11             | 9.1     | 147.2 | 0.77         |
| Q       | 40.82             | 7.3     | 154.8 | 0.67         |
| V       | 60.85             | 4.9     | 165.6 | 0.59         |
| W       | 93.32             | 3.2     | 173.5 | 0.54         |

Notes.

a Seven-year values; see Jarosik et al. (2011).

b $\lambda = c/\nu_{\text{J}}$.

c Brightness temperature calculated for a solid angle $\Omega_{\text{obs}} = 2.48 \times 10^{-8}$ sr at a fiducial distance of 5.2 AU. Temperature is with respect to blank sky: absolute brightness temperature is obtained by adding 2.2, 2.0, 1.9, 1.5, and 1.1 K in bands K, Ka, Q, V, and W, respectively (Page et al. 2003a). Jupiter temperatures are uncorrected for a small synchrotron emission component (see Section 3.2).

d Computed from errors in $\Omega_{\text{B}}$ (Jarosik et al. 2011) summed in quadrature with absolute calibration error of 0.2%.
Table 4

| Seasona | Start       | End         | ΔT/T (%) | % Maskeda | Mean Positionb |
|----------|-------------|-------------|----------|-----------|----------------|
|          |             |             |          |           | l              | b               |
| Meanb    | Scatterb    |             |          |           |                |                 |
| 1        | 2001 Oct 08 | 2001 Nov 22 | 0.11     | 0.28      | 0              | 194             | 13               |
| 2        | 2002 Feb 11 | 2002 Mar 27 | ...      | ...       | 95             | 189             | 5                |
| 3        | 2002 Nov 10 | 2002 Dec 24 | 0.13     | 0.28      | 0              | 214             | 40               |
| 4        | 2003 Mar 15 | 2003 Apr 29 | 0.28     | 0.48      | 60             | 206             | 32               |
| 5        | 2003 Dec 11 | 2004 Jan 23 | 0.01     | 0.22      | 0              | 254             | 59               |
| 6        | 2004 Apr 15 | 2004 May 30 | 0.01     | 0.32      | 0              | 237             | 55               |
| 7        | 2005 Jan 09 | 2005 Feb 21 | 0.00     | 0.27      | 12             | 311             | 56               |
| 8        | 2005 May 16 | 2005 Jul 01 | 0.08     | 0.39      | 0              | 294             | 60               |
| 9        | 2006 Feb 07 | 2006 Mar 24 | 0.13     | 0.29      | 18             | 344             | 35               |
| 10       | 2006 Jun 16 | 2006 Aug 02 | 0.03     | 0.45      | 0              | 335             | 43               |
| 11       | 2007 Mar 10 | 2007 Apr 24 | 0.41     | 0.31      | 0              | 2              | 9                |
| 12       | 2007 Jul 19 | 2007 Sep 03 | 0.11     | 0.49      | 42             | 356             | 17               |
| 13       | 2008 Apr 11 | 2008 May 27 | 0.20     | 0.37      | 0              | 17             | −19              |

Notes.
a Season 2 omitted from analysis because Jupiter is aligned with the Galactic plane.
b Mean of the percentage temperature change among the DAs for each season, relative to the seven-year mean.
c 1σ scatter in the percentage temperature change among the DAs for each season.
d Typical percentage of available observations within 0.5 of planet center which are excluded from analysis because of Galactic plane masking.
e Approximate seasonal Jupiter position in Galactic coordinates at mean time of unmasked observations.

The estimated signal-to-noise is low, with no significant detection of linear polarization of the synchrotron emission at 15 and 22 GHz has been detected by observations in any differencing assembly. Linear polarization of the synchrotron polarization fraction at 22 GHz, but do not provide any further constraint.

### 3.3. Mars

Mars’ value as a calibrator depends upon the accuracy to which its whole-disk brightness variations (both apparent and intrinsic) can be modeled. Much of the perceived variability from earth-orbit is attributable to geometrical factors: the apparent phase as seen by the observer and changes in solar irradiance as Mars’ distance from the Sun varies in its elliptical orbit (Wright 1976). There are a number of additional complexities, however. The day/night cycle imparts a significant rotational modulation to the observed temperature as the surface heats and cools. In the infrared, variable atmospheric effects including molecular line absorption and dust storms can be of importance. Additionally, the Martian surface is itself far from homogenous, with polar ice-caps of changing extent and variations in albedo and thermal inertia on relatively small scales (Putzig & Mellon 2007; Christensen et al. 2001).

Planetary science studies notwithstanding, the astronomical community has most consistently referenced two basic models when calibrating to Mars: the “Wright model” (Wright 1976; Wright & Odenwald 1980; Wright 2007) and the “Rudy model” (Rudy et al. 1987; Muhleman & Berge 1991), both developed before the current level of detail available from orbiters such as Mars Global Surveyor (MGS). In the thermal emission regime ($\lambda \gtrsim 10 \mu m$), the planet’s brightness temperature can be computed to first order as re-emission of absorbed solar energy by a surface layer with a characteristic albedo, emissivity and thermal inertia (de Pater 1990). The Wright model uses this as Mars Global Surveyor (MGS). In the thermal emission regime ($\lambda \gtrsim 10 \mu m$), the planet’s brightness temperature can be computed to first order as re-emission of absorbed solar energy by a surface layer with a characteristic albedo, emissivity and thermal inertia (de Pater 1990). The Wright model uses this to model the planet’s brightness temperature as a function of position on the longitude/latitude grid. Typical errors on $T_b$ quoted for the Wright model are ±5%, or about ±10K, and those for the Rudy model at 5%–10%. We have chosen in this paper to compare the WMAP observations against predictions from the Wright model, primarily because of its long history of use and readily available model code (Wright 2007), but also because the seasonal brightness temperatures quoted for WMAP are the resultant average over several weeks of data, which means we are only sampling mean properties at best. We have modified the 2007 Wright model code in three ways: (1) JPL ephemeris positions are substituted for the lower precision formulae originally used, (2) an option is added to use WMAP spacecraft positions rather than those of the Earth, and (3) computations are extended out to WMAP frequencies. The first two changes are not critical to the analysis, as the combined modifications introduce at most at 0.6 K difference from the original results. Typically the model predicts brightness temperatures at 3 mm which are a few Kelvins lower than those at 350 μm, and the temperature spread between the extrema of the 5 WMAP frequencies is quite low, of order 0.5 K.

Hill et al. (2009) presented the first five years of WMAP Mars observations at 94 GHz. Here we extend the W-band observations to seven years, and include the observations at the other four WMAP frequencies. Mean brightness temperatures for Mars at five frequencies and seven WMAP observing seasons derived from the seven-year data are presented in Table 6. After correcting to absolute brightness temperature and converting

Table 5

| DA     | Q/I (%) | U/I (%) | V/I (%) | Q/I (%) | U/I (%) | V/I (%) |
|--------|---------|---------|---------|---------|---------|---------|
| K1     | 0.306   | 0.658   | 0.428   | 0.726   | 0.464   | 1.62    |
| K2     | 0.181   | 0.408   | 0.191   | 0.293   | 0.263   | 0.352   |
| Q1     | 0.168   | 0.430   | 0.244   | 0.304   | 0.296   | 0.349   |
| Q2     | 0.151   | 0.428   | 0.062   | 0.297   | 0.163   | 0.411   |
| V1     | 0.149   | 0.358   | 0.462   | 0.252   | 0.486   | 0.263   |
| V2     | 0.143   | 0.305   | 0.067   | 0.223   | 0.158   | 0.292   |
| W1     | 0.040   | 0.319   | 0.393   | 0.233   | 0.395   | 0.234   |
| W2     | 0.156   | 0.380   | 0.188   | 0.264   | 0.245   | 0.317   |
| W3     | 0.006   | 0.397   | 0.377   | 0.277   | 0.377   | 0.277   |
| W4     | 0.058   | 0.371   | 0.311   | 0.273   | 0.316   | 0.277   |

Notes.

a Propagated error from $\sigma_Q$ and $\sigma_U$.
b Propagated error from $\sigma_Q$ and $\sigma_V$.
c $p_{\text{lin}} = \sqrt{(Q/I)_f^2 + (U/I)_f^2}$.
d Propagated error.
e $S/N = p_{\text{lin}}/\sigma(p_{\text{lin}})$. 
from Rayleigh–Jeans to Planck brightness temperature, the seven seasonal W-band averages are shown in comparison to the Wright model predictions at 3.2 mm in Figure 3. This plot is similar to Figure 15 of Hill et al. (2009), whose preliminary analysis found that the Wright model was a good predictor of the mean temporal variation, but the model $T_b$ seemed high by roughly 10%. Our results generally agree, but we find that multiplying the Wright model by a factor of 0.953 fits the seven-year data best. If one uses the Wright model tabulated at 350 μm, the plot looks nearly identical, but the scaling factor is 0.941, or about a 6% reduction. A previous comparison by Griffin et al. (1986) indicated that the 3 mm whole-disk observations of Ulich (1981) were within 7.5% of Wright model predictions at 350 μm. The first WMAP Mars observing season occurred during the time of the 2001 July–October massive global dust storm which elevated atmospheric temperatures in the mid-IR by nearly 40 K (Smith et al. 2002). The effect of dust storms on microwave data is expected to be less of a concern, but we did fit for the model scaling factor both with and without inclusion of the first observing season, with no significantly different results.

The uncertainties on the derived WMAP seasonal brightness temperatures increase with decreasing frequency, which follows as a result of decreasing signal-to-noise in the data. However, it is possible to extract a trend in temperature with frequency by finding within each season the ratio of the brightness temperature at each frequency to that at the W band, and then computing the mean over all seven observing seasons as a function of frequency. These means are plotted in Figure 4 in black. Errors are standard deviations of the mean. The weak frequency dependence can be characterized roughly as $ν^{-0.03}$, indicated by the blue line. The Wright model, processed in the same fashion, predicts almost no variation with frequency (red line). Such a frequency dependence could be attributed to an emissivity change of ~5% ± 2% over the wavelength interval. In a similar vein, a weak 5% ± 3% decline in surface emissivity with increasing wavelength was noted by Burgdorf et al. (2000)

in the 50 to 180 μm range, based on analysis of Infrared Space Observatory (ISO) observations of water vapor absorption lines. Some consideration was given to placing the WMAP observations in a wider context, with the goal of gaining further insight into the model parameters. A search was made for a dataset that would provide absolutely calibrated, whole-disk observations of Mars which spanned both sides of the thermal energy distribution peak and were taken over a reasonably contiguous interval of time. Mars data taken by the COBE/DIRBE instrument (Boggess et al. 1992; Hauser et al. 1998) for a 146 day interval (1990 April 28–September 20) most closely matched these requirements, although no analysis of the publicly available data appears to have been previously published. There are six DIRBE wavebands which sample the thermal emission portion of the Mars spectrum, with effective wavelengths of 12, 25, 60, 100, 140, and 240 μm. Of these, the

15 The Wright model predictions are tabulated as Planck brightness temperatures, which reconstruct the model flux assuming a blackbody with no limb darkening.

16 http://lambda.gsfc.nasa.gov/
25 μm observations cannot be used as an independent check of the Wright model, since the model itself was the ultimate source of the DIRBE absolute calibration in this band (S. Moseley & W. Glaccum 2009, private communication; Hauser et al. 1998). In addition, while the 12, 25, 140, and 240 μm detectors are well-behaved linear devices, the 60 and 100 μm detectors are known to suffer nonlinear response, and Mars is on the bright end of that response. DIRBE is a broadband photometer, and reports monochromatic flux values at the effective wavelength of each band assuming a constant source spectrum in νIν across the band. One must apply a “color correction factor” to the reported fluxes if the source spectrum is different from that assumed. The DIRBE Explanatory Supplement provides such factors for gray-body and power-law spectra. However, in the case of Mars, some of the DIRBE bands intercept known atmospheric absorption lines. A significant CO absorption centered at 15 μm lies well within the 12 μm passband, and grazes the blue edge of the 25 μm band. Numerous minor water vapor absorptions are known to occur at wavelengths sampled by the 60 and 100 μm bands (Sidher et al. 2000). We have used spectral data available from the MGS thermal emission spectrograph (TES) public archives17 and the ISO spectrum published by Sidher et al. (2000) to form approximate correction factors for the DIRBE data at these bands; only the 12 μm band required significant correction. For the 140 and 240 μm bands, color corrections were calculated using the spectrum predicted by the Wright model.

A mean flux at each DIRBE effective wavelength was evaluated over the 146 day interval, including application of color corrections and scaling to a fiducial solid angle at a distance of 1.5 AU (Table 7). Although the epochs of WMAP and DIRBE observations are separated by more than 10 years, the viewing geometry at the time of the DIRBE observations is most closely duplicated during WMAP observing season four. The WMAP mean brightness temperatures for this season were also converted to fluxes using the same fiducial solid angle, and both sets of data plotted as a spectrum in Figure 5. The spectra predicted by the Wright model for the mean time of the two epochs are also shown on the plot. For clarity, the quoted model errors of about ±5% are not shown on the plot. On the logarithmic scale needed to show both sets of data together, the two model spectra overlay each other. Within the quoted data and model errors, the DIRBE measurements at 60 and 100 μm do not match well with the model. The DIRBE 12 μm data deviate by a little more than 1σ, accounting for both data errors and model accuracy. In the case of the 60 and 100 μm bands, we suspect a nonlinear response to a bright object is the root cause. The 12 μm band has a low absolute calibration error, but there is a significant and uncertain color correction due to the CO2 atmospheric absorption. Ratios of the DIRBE fluxes to Wright model predictions are presented in Table 7; the major source of DIRBE error is that of the absolute calibration, which is also listed. DIRBE observations at 140 and 240 μm agree within the 10% calibration errors, but cannot be used to deduce any trend with frequency, such as seen by WMAP. We decided to forgo adjustments to the model at this point.

As currently implemented, the Wright model may be used to predict microwave observations at WMAP frequencies by applying a “post-processing” multiplicative scaling factor to the published values: Tnew = Tpub × fscal. For both model and data evaluated at 3.2 mm, we have already noted a scaling factor of 0.953. We use the mean ratios of the remaining four frequencies to W band (Figure 4) as scaling factors for these frequencies, which are in Column 2 of Table 8. The W-band observations can be reproduced to ~ 0.5%, with confidence decreasing with frequency to ~ 2% at the K band. Since the 3.2 mm model values we have computed are not published, we also provide scaling factors to the 350 μm temperatures, which are derived from the the scaling factor of 0.941 noted earlier and multiplied through by the 3.2 mm scaling ratios.

Differences between measurements and the Wright model at WMAP wavelengths are not unexpected. The Wright model was designed to predict infrared emission arising from the top layer of the Martian surface, whereas the microwave signal originates from subsurface layers of order several centimeters deep (de Pater 1990; Orton & Burgdorf 2003), with potentially different composition and compaction. This was recognized by Griffin et al. (1986) and Griffin & Orton (1993), who recommended a logarithmic interpolation between the Wright 350 μm prediction and the 3.3 mm brightness temperature.

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17 http://tes.asu.edu/
versus Mars–Sun distance fit of Ulich (1981), citing agreement with the Rudy model within 1.2% for a dielectric constant revised upward from 2.25 to 2.8. On average, the Ulich (1981) fit predicts brightness temperatures roughly 5% higher than the WMAP mean seasonal values at 3.2 mm. This suggests that the lower value for the dielectric constant is preferable. We obtained disk-averaged Rudy model predictions at lower value for the dielectric constant is preferable. We obtained mean seasonal values at 3.2 mm. This suggests that the fit predicts brightness temperatures roughly 5% higher than the WMAP observational means at the specified frequencies.

It should be noted that the WMAP observations provide model constraints only in the disk-averaged sense. The post-processing scaling of the Wright model suggested here simulates a frequency-dependent emissivity, which implies slow changes in mean subsurface properties with depth. In the Rudy model, which already incorporates subsurface sampling, use of model parameters derived from the radio data produces agreement with WMAP within a few percent. It is possible that this agreement could be improved either through the use of a revised dielectric function or updated thermal inertia and albedo maps. The thermophysical parameters used by the Rudy model are based on ~20 year old maps of thermal inertia and albedo from the infrared thermal mapper (IRTM) on board Viking (Muhleman & Berge 1991). More recent MGS maps of these quantities obtained using the TES instrument are available with roughly 10 to 40 times better spatial resolution, full planet coverage and approximately twice the signal-to-noise (Christensen 1998; Christensen et al. 2001). The surface albedo has been observed to have some time dependence: a visual comparison between the Viking IRTM and TES albedo maps shows alterations in the spatial pattern have occurred since the Viking mapping (Christensen et al. 2001).

3.4. Saturn

As with Mars, Saturn’s microwave brightness temperature varies considerably over time for near-Earth observers, primarily as a result of geometrical effects. Here the dominant factors are the observer’s changing viewing angle of the rings and projected disk of the oblate planetary spheroid.

The ring system presents the main difficulty in Saturn’s use as a calibrator in the microwave, although substantial progress has been made in understanding and modeling it. As evidenced by images from Hubble Space Telescope (HST) and data from orbiter and flyby missions such as Cassini and Voyager, Saturn’s ring system is complex and rich in detail. The brightest rings (A, B, C) are composed of objects typically less than 5 m in size (Marouf et al. 1983) and are composed primarily of water ices mixed with a small amount of impurities (Poulet et al. 2003, and references therein). Those portions of the rings between the observer’s line of sight and the planet serve to attenuate emission from Saturn’s disk. The rings also contribute to the microwave signal via a mix of scattering and thermal re-emission of planetary radiation. The crossover point between the two emission mechanisms occurs near 1 cm (Dunn et al. 2002; Schloerb et al. 1980; Epstein et al. 1980), with thermal emission dominating shortwards and scattering longwards. Optical depths have been measured at a variety of wavelengths: Dowling et al. (1987) found that the optical depth of the combined ABC rings is roughly gray over a wide frequency range. Voyager I radio occultation observations (Tyler et al. 1983) at 3.6 and 13 cm produced radial profiles of optical depth for the A and C rings and Cassini division, but only approximate results for portions of the B ring with $r > 1$. The most complex and recent modeling of microwave data is that of Dunn et al. (2002, 2005, 2007) who use a Monte Carlo radiative transfer code to simulate the scattered and thermal emission of the rings based on VLA and other high-resolution observations.

WMAP does not spatially resolve the individual components of the Saturn system, nor is the spectral coverage sufficient to definitively isolate ring scattering and thermal spectral regimes. However, the changes in viewing geometry with orbital phase can be used to break degeneracy between ring and disk components, especially as the viewing aspect of the rings becomes more “edge-on”. Over the currently available seven-year observing baseline, Saturn’s rings are seen at inclinations between $−28°$ and $−6°$; the sign convention indicates that the planet’s south pole is tilting slowly away from the observer as the $0°$ edge-on equatorial configuration is approached. Figure 6 illustrates the two extrema and Table 9 list mean times and ring opening angles for each observing season.

Hill et al. (2009) briefly discussed WMAP five-year W-band observations of Saturn, which sampled ring opening angles $B \leq −17°$. They found that the brightness temperature could be fit remarkably well with a simple sin $B$ dependence. This convenient relationship does not effectively characterize the behavior at lower inclinations, however, and so a more complex
formulation is needed for the seven-year data. We adopt a simple empirical model of Saturn’s microwave emission, variants of which have appeared in the literature for over 30 years (e.g., Klein et al. 1978; Epstein et al. 1980). The goal is to provide a predictive formula for the unresolved observed brightness of Saturn with as low an error as possible; however, given the WMAP data constraints, such a model will lack physical detail. At a given frequency ν, we assume a single temperature for the planetary disk, \( T_{\text{disk}}(\nu) \), and that all rings are characterized by the same temperature \( T_{\text{ring}}(\nu) \). The model variant we adopt allows for seven radially concentric ring divisions as defined by Dunn et al. (2002), which are based on optical depth variations observed by Voyager (Tyler et al. 1983). Each of the seven ring sectors has its own ring-normal optical depth \( \tau_{0,i} \), with \( 1 \leq i \leq 7 \), but each \( \tau_{0,i} \) is assumed to be both constant within its ring and frequency independent.

Those portions of the planetary disk which are obscured by ring cusps will have their emission attenuated by a factor \( e^{-\tau_{0,i} \csc B_i} \), where \( B \) is the ring opening angle seen by the observer. Thus at a given frequency and ring opening angle \( B \):

\[
T(\nu, B) = T_{\text{disk}}(\nu)[A_{\text{ud}} + \sum_{i=1}^{7} e^{-\tau_{0,i} \csc B_i} A_{\text{od},i} + T_{\text{ring}}(\nu)] \sum_{i=1}^{7} A_{r,i},
\]

where \( A_{\text{ud}}, A_{\text{od},i}, \) and \( A_{r,i} \) are the projected areas of the unobscured disk, the portion of the disk obscured by ring \( i \), and \( r^{th} \) ring, respectively. These areas are normalized to the total (obscured+unobscured) disk area. \( T_{\text{ring}}(\nu) \) is an observed brightness temperature and hides such physical details as ring emissivity and the apportionment of the scattering versus thermal emission. The assumption of a single mean ring temperature is a convenience rather than reality (Spilker et al. 2006; Grossman et al. 1989; Dunn et al. 2002). However, the apportionment between individual rings is not critical to the model fit, as it only depends on the summed total ring emission. Potential contributions to modeling error from nonuniform planetary disk emission are discussed later in this section.

The WMAP brightness temperatures in Table 9 are sorted by frequency band and \( B \) and then a single simultaneous fit for the model parameters is made. Two separate fits were tried, differentiated from one another in the handling of the ring optical depth. In one fit, the \( \tau_{0,i} \) were held fixed at the values chosen by Dunn et al. (2002; Table 10), and the ten disk and ring temperatures (for each of 10 DAs) were solved for. In an alternate fit, the relative ratios between the \( \tau_{0,i} \) were fixed as per the table, but a single \( \tau_{0,\text{max}} \) was solved for in addition to the ten free temperatures. Both fits returned similar results, with reduced \( \chi^2 \) of \( \sim 1.2 \) for \( \sim 100 \) degrees of freedom. We show only the results for the fixed-r fit.

The disk and ring brightness temperatures derived from this model fit are presented in Table 11. Formal errors for the ring and disk temperatures at lower frequencies are higher because the ring contribution is smaller and there is a larger covariance between the two components. The model fit and residuals are shown in Figure 7. The model reproduces the observations to within \( \sim 3\% \), but observations closer to \( B = 0^\circ \) would better constrain the disk temperatures and so reduce the covariance between the disk and rings. The parameterization chosen for the
ring optical depths, together with the incomplete sampling of the ring system orientation, allows for alternate models which would fit the data equally well but return somewhat different mean disk and ring temperatures. This systematic is not reflected in the formal fitting errors in Table 11. In order to assess the magnitude of this error, we explored a small number of model variants. The model which fit the data equally well but returned temperatures with the largest differences compared to Table 11 consisted of a combined ABC ring represented by a single $t_0$, which was a free parameter in the fit. Disk temperatures derived for this model were $\sim 2.5$ K higher, and ring temperatures $\sim 1$ K lower. As a conservative approach, we additively combine this estimated systematic error with the formal fitting errors to produce the "adopted error" columns in Table 11. The derived disk and ring temperatures match well with those already in the literature. Figure 8 shows the WMAP derived disk temperatures in context with the compendium of Klein et al. (1978) plus more recent interferometric observations. The ring temperatures also compare well with those measured directly from high-resolution images of the ring ansae (Dunn et al. 2005; Schloerb et al. 1980; Janssen & Olsen 1978); see Figure 9. Figure 10 illustrates the percentage contribution of the ring to our total model, which sums the ring emission and attenuation of disk radiation, as a function of frequency and ring inclination $B$.

The empirical model described here assumes Saturn’s mean whole-disk temperature is time invariant at each frequency. The presence of band-like structures (which can persist for years) and latitudinal brightness gradients at the $\sim 5\%$ level have been noted by several observers at wavelengths of 2 cm and longward (Grossman et al. 1989; de Pater & Dickel 1991; van der Tak et al. 1999). There is less discussion in the literature of disk temperature structure and/or variability at the frequencies observed by WMAP: there have been no reports of bands or localized structures, but some indication of north/south latitudinal brightness differences. Within the seven-year epoch under consideration, Dunn et al. (2005) observed a latitudinal disk brightness gradient at 3 mm, such that the north pole was brighter than the south by $\sim 5\%$. They interpreted differences between their 1.3 mm and 3 mm data, taken roughly 4 months apart, as possible evidence for atmospheric changes on week to month timescales. In order to estimate potential model bias caused by the assumption of a uniform disk temperature, Saturn seasonal brightness temperatures were simulated using geometrical models similar to those described in this section, with the addition of a disk latitudinal gradient as described by Dunn et al. (2005). If one makes the assumption that such a temperature gradient is persistent over seven years and exists at all WMAP frequencies, then such structure would produce a temperature behavior with inclination which is asymmetric
to resolve the Phoebe ring, with reason, the adopted errors in Table 11 have not been adjusted to the mean whole-disk temperature. This estimate is mean ring temperature biased by less than 1 K, with an unbiased imaging at 24 and 70 μm (Spitzer). Seven-year observing seasons, the model fit returns a WMAP temperature gradient. For a simulated dataset matching the use the ring model component to compensate for the disk model fit which assumes a constant disk temperature would full B range, this asymmetry would not be evident, and a model fit which assumes a constant disk temperature would use the ring model component to compensate for the disk temperature gradient. For a simulated dataset matching the WMAP seven-year observing seasons, the model fit returns a mean ring temperature biased by less than 1 K, with an unbiased recovery of the mean whole-disk temperature. This estimate is of uncertain quality, however, because it is based on a snapshot of Saturn at one wavelength and a narrow time window. For this reason, the adopted errors in Table 11 have not been adjusted to reflect this potential effect.

An extended, low optical depth dust ring associated with Saturn’s moon Phoebe was recently discovered using Spitzer imaging at 24 and 70 μm (Verbiscer et al. 2009). With a quoted radial extent between at least 128 and 207 Saturn radii, or roughly 1° in apparent diameter, it would be possible for WMAP to resolve the Phoebe ring, with W band as the best chance for doing so. However, no signal from the ring was detected by WMAP. Properties of the grains are not well specified, but naive estimates assuming typical dust emission and optical depth frequency dependencies would predict temperatures at 94 GHz of less than 1 μK, well below achievable noise levels of about 300 μK (1σ).

3.5. Uranus and Neptune

With their lower brightness, lack of a dominant ring system, and small solid angle, Uranus and Neptune are used as primary calibrators in infrared through radio wavebands for both ground- and space-based instruments. Spectral coverage in the microwave is somewhat undersampled, however, leaving room for interpretation in atmospheric modeling efforts. The microwave spectra of Uranus and Neptune lack the broad NH3 absorption centered near 24 GHz which is characteristic of Jupiter and Saturn. At millimeter wavelengths, collision-induced absorption by H2 is considered the dominant continuum opacity source. CO rotational absorptions have been observed for Neptune in the sub-millimeter (Marten et al. 2005). At centimeter wavelengths, ammonia (which is depleted relative to solar nitrogen levels) and hydrogen sulfide are the main opacity contributors (Deboer & Steffes 1996; Spilker 1995; de Pater et al. 1991). Of special note is Uranus’ unique 98° obliquity, which allows for a slowly changing pole-to-pole panorama of the planet as it moves in its 84 year orbit, and may also play a role in determining atmospheric conditions.

For selected frequencies, observational databases spanning decades have permitted characterization of the variability of these two planets. Uranus in particular has exhibited long-term whole-disk temperature changes since 1966 which correlate with the viewing aspect of the south pole. After accounting for geometrical solid angle changes, Kramer et al. (2008) reported a gradual temperature drop of order 10% over 20 years (1985–2005) at 90 GHz. This is interpreted as a true integrated-disk temperature change, as the 1985 face-on contribution from the bright south pole progressively morphs into a 2007 view dominated by colder equatorial regions. Similar findings, with similar phasing albeit different amplitudes, have been reported in the radio (Klein & Hofstadter 2006) and visible (Hammel & Lockwood 2007). There is weaker evidence that some portion of variability in the light curves is attributable to changes deep in the atmosphere (Klein & Hofstadter 2006; Hofstadter & Butler (2003) used VLA 2 and 6 cm “snapshots” of the disk over several years to argue for opacity changes in zonal bands. Neptune’s microwave variability is less well documented, although there is ample evidence for variability in the visible and near-IR, as summarized by Hammel & Lockwood (2007). Kramer et al. (2008) find the 90 GHz integrated disk temperature to be constant to within ~8% over 20 years.

Peak WMAP antenna temperatures for these distant “ice giants” range from roughly 1 mK at the W band to ~0.2 mK.
at the K band. The signal-to-noise for individual observations of these objects is low (~0.3 at the W band, ~0.14 at the K band), resulting in large statistical errors in single-season disk temperature determinations. Tables 12 and 13 present the single-season brightness temperatures computed for Uranus and Neptune. Brightness temperatures are listed per frequency rather than per DA as a means of boosting signal-to-noise for those frequencies with multiple DAs. Temperatures for Uranus observing seasons four and five exhibit somewhat larger error bars than other seasons. For these two seasons, there was a reduction in the number of observations available for analysis because data quality checks excluded observations in close proximity to Mars sky coordinates.

Sub-WMAP latitudes for Uranus range between −30° and 6° over our seven-year baseline. Linear correlations of $T_b$ against both sub-WMAP latitude and time produced no statistically significant trend other than a flat line. This is not surprising given that the tightest seasonal temperature errors are of order 10%, which encompasses the entire twenty-year range of variation seen in the 90 GHz light curves of Kramer et al. (2008). We performed similar correlations for Neptune, with again the same null variability result. Note, however, that the sub-WMAP latitude for this planet is relatively unchanged over the epochs of observation. With no discernable variability over the observing baseline, we computed seven-year means of the disk brightness for each planet; these are listed as the last line in Tables 12 and 13. These seven-year means in turn may be compared to observations in the literature and placed in context with the microwave spectra in general.

Figure 11 overplots the seven-year mean WMAP Uranus temperatures at K, Ka, Q, V, and W center frequencies on a composite spectrum derived from several sources in the literature. Points are color-coded to reflect the decade in which observations were taken. Data have been culled from Griffin & Orton (1993), Muhleman & Berge (1991), Greve et al. (1994), Cunningham et al. (1981), and Gulkis et al. (1978). Also included is the mean 3.5 cm value from the 1966–2002 compilation of Klein & Hofstadter (2006), with a single large error bar indicating the ~30 K peak-to-peak variation in the light curve. Within the quoted errors, there is general agreement between the WMAP observations and those taken at previous epochs. The WMAP observations show a “dip” in Ka-band temperature compared to neighboring frequencies. Although not of high statistical significance, a feature of this nature is clearly of interest. A literature search for corroborating observations near 30 GHz only returned those few acquired in the late 1960s, listed in Table 1 of Gulkis et al. (1978). For a variety of reasons, more recent observations would be preferable, but the older epoch does have the advantage of sharing a similar viewing geometry to that of the WMAP data. These older observations are plotted in gray in the Figure, and agree well with the WMAP measurements, but also do not define a “dip” at high statistical significance. Although suggestive of an interesting atmospheric opacity constraint for future study, the possibility of such a feature has gone unremarked in the literature.

A composite microwave spectrum for Neptune is shown in Figure 12. The color coding again indicates observational epoch, with ground-based data taken from de Pater & Richardson (1989), de Pater et al. (1991), Muhleman & Berge (1991), Griffin & Orton (1993), Hofstadter (1993), and Greve et al. (1994). Deboer & Steffes (1996) provide a summary of observations in the 1990s. Observations with error bars larger than about 30 K are not included in the plot. WMAP-derived temperatures for the Q band agree well with those of Greve et al. (1994), while the 94 GHz observations lie on the upper envelope of data taken in the 1970s and 1980s. WMAP observations occur when Neptune’s south pole is most fully viewable. The observational error on the seven-year W-band mean is ~8%, which is equivalent to the level to which Klein & Hofstadter (2006) claimed 20 year stability.

Reasonable temperature error bars for the WMAP Uranus and Neptune observations are only achieved through averaging the seven-year data. Observers wishing to use these data for
calibration of observations taken outside of the 2001–2008 epoch should keep in mind the variability and related geometric issues described above.

4. CELESTIAL SOURCES

Non-variable, spatially isolated fixed celestial calibrators for millimeter wavelengths are not common. At high Galactic latitude, bright sources are predominantly identified as some form of AGN/QSO, which are prone to outbursts and variability on a wide range of timescales and frequencies. Brighter sources in the Galactic plane tend to be H II regions (which may not be “point-like”) or supernova remnants (SNRs) with potential variability. At moderate spatial resolution, confusion with neighboring diffuse and compact sources in the Galactic plane can be an issue for background subtraction.

Five sources were chosen for study out of an original list which included some of the brightest sources from Baars et al. (1977) and Ott et al. (1994), in addition to the brightest, least variable objects from the seven-year WMAP source catalog (Gold et al. 2011). The five selected sources are listed in Table 14. Some of the sources which were initially considered but ultimately rejected, primarily because of low background contrast, included 3C286, NGC 7027, 3C84, 3C218, 3C123, and 3C147. There are unfortunately few suitable calibration sources in the Southern hemisphere with a long-term history of observation.

4.1. Data Processing and Analysis Methods

Flux densities of the selected sources are measured from the seven-year sky maps at HEALPix\textsuperscript{19} resolution 9 (Nside = 512). For each frequency band, the azimuthally symmetrized beam profile (see Section 3.1) is convolved with a sky map pixel to produce a map-based beam template. The sum of the pixel-convolved beam template plus a sloping planar base level is fit to the Stokes $I$, $Q$, and $U$ sky map data at each source position, using pixels within 3.5 times the beam width $\sigma$ (1.5 times the FWHM) in each band. The peak source temperature from each fit is converted from thermodynamic temperature to Rayleigh–Jeans brightness temperature and then translated to a source flux density using a conversion factor $\Gamma$ that is a weak function of the source spectral index (Jarosik et al. 2011). For point sources, this method of flux measurement is more accurate than the aperture photometry method as used for example by Page et al. (2003b) for Tau A. The WMAP beam profiles have extended wings (Hill et al. 2009), so an aperture radius $\gtrsim$3 times the beam FWHM should be used and the results are more susceptible to error due to background confusion.

The uncertainty in flux density is calculated as the quadrature sum of (1) map measurement uncertainty, (2) the uncertainty in $\Gamma$ (0.5% to 0.7% depending on the band), and (3) the 0.2% absolute calibration uncertainty. For Stokes $I$, map measurement uncertainty is estimated from the rms fit residual in the fit region. The Stokes $I$ residuals generally appear to be dominated by beam asymmetry effects, but also include background confusion and noise. (The source profiles in the maps are asymmetric due to asymmetry in the instantaneous beam profiles and the nonuniform distribution of scan angles over a year for sources away from the ecliptic poles.) For Stokes $Q$ and $U$, map measurement uncertainty is calculated either from the $I\sigma_i$ source peak uncertainty and base level uncertainty from the beam fitting or as the $\sigma_Q$ or $\sigma_U$ flux times the fractional map measurement uncertainty for $I$, whichever is largest. The latter method is the estimated uncertainty in $Q$ or $U$ due to beam asymmetry effects, assuming the fractional uncertainty is the same in $Q$ or $U$ as it is in $I$. The flux determination was tested on simulated sky maps containing a population of point sources with no other signals and no noise, generated using WMAP beam window functions as described in Wright et al. (2009). Recovered flux densities were accurate to about 0.1% or better, except in W band where

\textsuperscript{19} WMAP sky map products are in HEALPix format; see http://healpix.jpl.nasa.gov/. HEALPix divides the sky into pixels of equal area. The number and spacing between pixel centers depends on the chosen resolution. Nside = 512 corresponds to a pixel area of $\approx 3.995 \times 10^{-6}$ sr, with a mean spacing of 6.87 arcmin between pixel centers.
the recovered fluxes tended to be larger than the input fluxes by up to 1%. This is allowed for by including an additional 1% uncertainty term in the quadrature sum for W band.

Fractional year-to-year variability for the selected sources has been obtained using sky maps for individual years 1–7. To remove confusion noise from the CMB and Galactic foregrounds, we subtract the seven-year average map from each individual map. The flux difference \( \Delta F_i \) for the \( i \)th year for each source in each band. Uncertainty in \( \Delta F_i \) is calculated from the quadrature sum of the source peak uncertainty and the base level uncertainty. The flux difference is divided by the mean flux from the seven-year period for each source in each band. At 43 GHz, VLBA monitoring showed an increase of 0.57 Jy for the core region between 2008 January and April 2009. For 3C58, Green (1987) reported an increase of 0.21% per year for 3C58, and 0.54% per year for 3C274. The limit for Cyg A is consistent with the limit of 0.1% per year found by Hafez et al. (2008) at 33 GHz for the period 2001 March to 2004 May. For 3C58, Green (1987) reported an increase of 0.32% ± 0.13% per year at 408 MHz from 1967 to 1986.

Significant yearly flux variation is not seen for Cyg A and 3C58; the rms year-to-year variation is consistent with the uncertainties in each band. The lowest rms variation is in the K band, and is 0.27% for Cyg A and 0.33% for 3C58. Carilli & Barthel (1996) give an upper limit of 10% on Cyg A core variability from observations at 5, 15, and 90 GHz over timescales from 10 months to 15 years. The core contributes ≤10% of the total flux at WMAP frequencies (e.g., Robson et al. 1998). For 3C274 there is evidence for year-to-year variability of about 2% in the K, Ka, and Q bands. The rms variation is 1.8 to 2.6 times the mean uncertainty in these bands, and the variations are correlated from band to band. Previous observations of 3C274 have shown greater variability. At 90 GHz, Steppe et al. (1988) reported a decrease of 1.4 Jy for the core between 1985 June and 1986 August, which corresponds to ~17% of the total source flux. At 43 GHz, VLBA monitoring showed an increase of 0.57 Jy for the core region between 2008 January and April (Wagner et al. 2009), which corresponds to 4% of the total flux. Smaller core flux variations, less than 1% of the total flux, have been observed at lower frequencies (Morabito et al. 1988; Junior & Biretta 1995; Harris et al. 2009).

Spectra of the seven-year WMAP fluxes together with previous measurements from the literature are shown in Figures 14–18. For Cas A, we have scaled the WMAP fluxes, the Archeops fluxes of Desert et al. (2008), the SCUBA fluxes of Dunne et al. (2003), and the BLAST fluxes of Sibthorpe et al. (2010) to epoch 2000 using a secular variation of −0.53% per year. These are plotted with previous measurements that were scaled to epoch 2000 by Hafez et al. (2008) using frequency-dependent scaling. For Tau A, we have scaled previous measurements from Macias-Perez et al. (2010) to the epoch of the WMAP data using a secular variation of −0.167% per year at 33 GHz from 2001 to 2004. Dependence of the Cas A decrease on frequency and epoch has recently been discussed by Reichart & Stephens (2000) and Hafez et al. (2008). For Tau A, we find a somewhat higher rate of decrease than that of 0.18% ± 0.01% per year found by Vinyaikin & Razin (1979a, 1979b) at 927 MHz from 1962 to 1977 and 0.167% ± 0.015% per year found by Aller & Reynolds (1985) at 8 GHz from 1968 to 1984. Hafez et al. (2008) found a decrease of 0.22% ± 0.07% per year at 30 GHz from 2002 January to 2004 September.

No significant secular trends are seen for the other sources, with 3σ upper limits in the K band of 0.12% per year for Cyg A, 0.21% per year for 3C58, and 0.54% per year for 3C274. Significant yearly flux variation is not seen for Cyg A and 3C58; the rms year-to-year variation is consistent with the uncertainties in each band. The lowest rms variation is in the K band, and is 0.27% for Cyg A and 0.33% for 3C58. Carilli & Barthel (1996) give an upper limit of 10% on Cyg A core variability from observations at 5, 15, and 90 GHz over timescales from 10 months to 15 years. The core contributes ≤10% of the total flux at WMAP frequencies (e.g., Robson et al. 1998). For 3C274 there is evidence for year-to-year variability of about 2% in the K, Ka, and Q bands. The rms variation is 1.8 to 2.6 times the mean uncertainty in these bands, and the variations are correlated from band to band. Previous observations of 3C274 have shown greater variability. At 90 GHz, Steppe et al. (1988) reported a decrease of 1.4 Jy for the core between 1985 June and 1986 August, which corresponds to ~17% of the total source flux. At 43 GHz, VLBA monitoring showed an increase of 0.57 Jy for the core region between 2008 January and April (Wagner et al. 2009), which corresponds to 4% of the total flux. Smaller core flux variations, less than 1% of the total flux, have been observed at lower frequencies (Morabito et al. 1988; Junior & Biretta 1995; Harris et al. 2009).
all frequencies. Results are not significantly different if $-0.22\%$ per year is used. Table 17 presents parameters from fits to the spectra for WMAP data alone and for the combined data. The two fits are generally consistent within their uncertainties over the WMAP frequency range. Some notes on the individual sources follow.

Cas A. A slightly curved spectrum gives a better fit to the combined data than a power law (chi-squared per degree of freedom $\chi^2 = 1.20$ compared to $\chi^2 = 2.13$ for a power law). The flattening of the spectrum with increasing frequency was previously noted by Hafez et al. (2008). This may be consistent with observations of spatial variations of the spectrum in Cas A (e.g., Wright et al. 1999, Anderson & Rudnick 1996). Wright et al. (1999) presented spectra of 26 brightness peaks from maps with 7" resolution at 1.5, 5, 28, and 83 GHz. The data were mostly consistent with power-law spectra, with spectral indices ranging from $-0.75$ to $-0.95$. (For comparison, the overall spectral index from a power-law fit to our integrated spectrum from 1.4 to 93 GHz is $-0.73$). Such a variation will lead to curvature in the integrated spectrum. Wright et al. (1999) also found curvature for some of the brightness peaks with the spectra progressively flattening at the higher frequencies, and noted that such curvature is expected from models of particle acceleration in cosmic ray modified shocks (Reynolds & Ellison 1992).

Within the WMAP frequency range, all of the epoch 2000 scaled fluxes are consistent within the uncertainties with the fit to the combined data. This includes the WMAP fluxes, the
Figure 13. Fractional yearly flux variation measured for the celestial calibrators over the WMAP mission. Parameters of the linear fits are listed in Table 16.

### Table 17

| Source | Data       | Frequency Range (GHz) | Fit Type $^a$ | a           | b           | c           | d           |
|--------|------------|-----------------------|---------------|-------------|-------------|-------------|-------------|
| Cas A  | WMAP only  | 22–93                 | Power law     | 2.204 ± 0.002 | −0.712 ± 0.018 | ⋯           | ⋯           |
| Cas A  | Combined$^b$ | 1.4–250              | Curved        | 2.040 ± 0.002 | −0.682 ± 0.011 | 0.038 ± 0.008 | ⋯           |
| Cyg A  | WMAP only  | 22–93                 | Power law     | 1.480 ± 0.003 | −1.172 ± 0.020 | ⋯           | ⋯           |
| Cyg A  | Combined   | 2–94                  | Power law     | 1.482 ± 0.003 | −1.200 ± 0.006 | ⋯           | ⋯           |
| Tau A  | WMAP only  | 22–93                 | Power law     | 2.502 ± 0.005 | −0.350 ± 0.026 | ⋯           | ⋯           |
| Tau A  | Combined$^c$ | 1–353              | Power law     | 2.506 ± 0.003 | −0.302 ± 0.005 | ⋯           | ⋯           |
| 3C58   | Combined   | 0.04–83000            | Rolloff       | 33.7 ± 0.7   | −0.053 ± 0.013 | 0.021 ± 0.006 | 0.913 ± 0.045 |
| 3C274  | WMAP only  | 22–93                 | Power law     | 1.159 ± 0.005 | −0.731 ± 0.030 | ⋯           | ⋯           |
| 3C274  | Combined   | 0.4–93                | Curved        | 1.154 ± 0.005 | −0.733 ± 0.013 | 0.050 ± 0.008 | ⋯           |

Notes.

$^a$ Power law: \( \log S(\text{Jy}) = a + b \log (\nu/40 \text{ GHz}) \), Curved: \( \log S(\text{Jy}) = a + b \log (\nu/40 \text{ GHz}) + c \log^2 (\nu/40 \text{ GHz}) \), Rolloff: S(\text{Jy}) = a (\nu/1 \text{ GHz})^b / (1 + c (\nu/1 \text{ GHz})^b) \).

$^b$ The combined data for Cas A were scaled to epoch 2000.

$^c$ The non-WMAP data for Tau A were scaled to epoch 2005.

Absolutely calibrated fluxes from Janssen et al. (1974) at 22.29 GHz and Mason et al. (1999) at 32 GHz, the 33 GHz flux from Hafez et al. (2008), which is calibrated using the five-year WMAP Jupiter temperature, and the 86 GHz flux from Liszt & Lucas (1999), which is calibrated using the Ulich (1981) Jupiter temperature.

Above 300 GHz, there is excess emission above that expected for synchrotron emission, which has most recently been interpreted as emission from cool dust by Sibthorpe et al. (2010). The 353 and 545 GHz fluxes from Archeops (Desert et al. 2008) are much higher than the 600 GHz flux from BLAST (Sibthorpe et al. 2010) and the 353 and 666 GHz fluxes from SCUBA (Dunne et al. 2003). The Archeops measurements were made with a larger beam (~12′ compared to ~20′ or better for SCUBA and BLAST) and appear to be affected by dust emission that is not associated with Cas A.

The WMAP 23 GHz (K band) polarization map for Cas A exhibits unexpected structure. Figure 19 shows seven-year mean intensity and polarization images centered on each source at each of the five WMAP frequency bands. These images are 4.15 on a side, have not been background subtracted, and are scaled such that brighter pixels are black. The polarization (P) image for Cas A shows an irregular ~0.15 mK ring at a radial distance roughly 40′–50′ from the source position. The angular
The extent of Cas A is $\sim 5'$ (Table 14), leaving the reality of the ring feature in question. We have attempted to simulate this feature under the hypothesis that it is an artifact introduced by a combination of beam and source spectrum characteristics. Cas A is a steep-spectrum source. As a result of effective frequency differences between the two K-band radiometers (Jarosik et al. 2003b), the K11 radiometer (fed by the axial OMT port) has an FWHM roughly 3% wider than that of K12 (which is fed by the lateral OMT port), and the peak observed signal in K11 is a few percent higher than that of K12. Simulated beam maps for the two K-band radiometers were generated separately using Jupiter data as a template, and then individually scaled to peak values representative of Cas A. The difference between the two beams as a function of azimuthal angle and radial distance from beam center can be used to compute a rough estimate of induced Cas A polarization signal, under the assumption of complete scan-angle coverage. Figure 20 shows the results of such a simulation, which produces a feature with an approximately correct peak position (near $50'$), but slightly wider and 30%–40% brighter than that shown in the data image. A more complete simulation would include scan-angle coverage effects, which in this scenario are presumed responsible for the gaps in the ring. This is the only known instance of an apparent artifact in WMAP polarization data.

Cyg A. The fluxes from Janssen et al. (1974) at $22.29$ GHz, Wright & Birkinshaw (1984) at $89$ GHz, and Wright & Sault (1993) at $94$ GHz are consistent with the WMAP results. The flux from Hafez et al. (2008) at $33$ GHz is lower than WMAP Ka-band flux by $2.7\sigma$, taking both flux uncertainties into account. We found that excluding the Hafez et al. (2008) flux from the power-law fit to the combined data improved $\chi^2$ from 2.89 to 0.79, so it was excluded for the fit plotted in Figure 15 and the fit parameters given in Table 17. Most of the measurements above $100$ GHz in Figure 15 are fluxes summed over the core and two hot spots in the radio lobes. These are probably valid measurements of the total flux, since the contribution of extended emission from the steep-spectrum lobes appears to be small or negligible at these frequencies. At $230$ GHz, Salter et al.
(1989b) found that the integrated flux over the entire source was only about 10% greater than the summed flux of the hot spots and core, which did not amount to a significant detection of emission from the lobes.

**Tau A.** The WMAP flux agrees with that of Janssen et al. (1974) at 22.29 GHz and with that of Hafez et al. (2008) at 33 GHz. Flux measurements from three-year WMAP sky maps by Macias-Perez et al. (2010) are consistent with our results in the K–V bands, but their W-band measurement is 2.8σ greater than ours. The difference is probably due to difference in background subtraction error.

Tau A has been recommended as a polarization calibrator for CMB experiments by Aumont et al. (2010), who report a polarized flux density of 14.5 ± 3.2 Jy at 90 GHz. The WMAP value at 93 GHz is 16.6 ± 0.7 Jy. For a 10’ beam, Aumont et al. (2010) predict a position angle of 148.8 ± 0.2 (statistical) ±0.5 (systematic) in equatorial coordinates. The WMAP value at 93 GHz is 148.9 ± 0.7 (statistical) ±1.5 (systematic). These measurements and previous position angle measurements integrated over the source are shown as a function of wavelength squared in Figure 21. A linear fit to the data gives an intrinsic polarization position angle of 148.5 ± 0.3 and a rotation measure of −24.1 ± 0.2 rad m⁻². This mean rotation measure appears to be consistent with the rotation measure map obtained by Bietenholz & Kronberg (1991) from VLA observations at 1′/8 resolution. They found a large-scale rotation measure of ~ −21 rad m⁻² that they attribute to the interstellar medium, and from the observed depolarization they inferred absolute rotation measure values of a few hundred rad m⁻² in unresolved filaments.

López-Caniego et al. (2009) report polarized flux densities they measured from 5-year WMAP data that are smaller than the values in Table 15 by 9%, 15%, 28%, and 67% at 23, 33, 41, and 61 GHz, respectively. For Cas A, Cyg A, and 3C274, their polarized fluxes agree with those in Table 15 within the uncertainties.

3C58. The WMAP data show the spectral steepening first suggested by the 84 GHz measurement of Salter et al. (1989a) and confirmed by the upper limits of Green & Scheuer (1992) in the infrared. Our adopted form for the spectrum transitions between a low-frequency power law and a high-frequency power law, and gives a good fit to the combined radio to infrared data. Our fit gives a change in spectral index of about 0.9. Additional steepening is needed to explain the observed X-ray spectrum, and Slane et al. (2008) suggested there is a second spectral break somewhere in the infrared. They presented model calculations in which the break at ~100 GHz is due to a break in the electron spectrum injected into the nebula and the higher frequency break is due to synchrotron losses.

**Figure 18.** Spectrum of 3C274. The red symbols show WMAP data. The black symbols show data from Baars et al. (1977) and blue symbols show data from Ott et al. (1994). Black curve is a fit to the combined 0.4–93 GHz data of the form log S(Jy) = a + b log ν + c log²ν; coefficients are provided in Table 17.

**Figure 19.** Sky-fixed calibration sources in temperature and in polarization. Each picture is 4′15 in a side, and the vertical direction is aligned with Galactic north. Sources are labeled along the top, and frequency bands are labeled along the left side. Bright pixels are displayed as black. Left: Stokes I logarithmically scaled; peak pixel values in the K band are 60.8, 19.3, 95.8, 5.4, and 7.2 mK thermodynamic, respectively, for the five sources, at a native resolution of HEALPix nside = 512. Right: polarization P = (Q² + U²)¹/², where Q and U are Stokes parameters, smoothed with a Gaussian ofFWHM = 13.5. Scaling is linear between 0 and 0.25 mK thermodynamic, except for Tau A, where scaling is linear between 0 and 1 mK thermodynamic. Green arrow: north in the equatorial coordinate system. Red bars: polarization direction in a square pixel 39′ wide, shown only where the S/N of P is greater than ~2. The broken ring around Cas A in the K band is spurious and results from beam ellipticity coupled with effective frequency differences between the two orthogonally polarized K-band radiometers.
Figure 20. Simplistic simulation of a false polarization signal which would resemble a ring encircling Cas A at a radius of ~50′. The black line is the radial profile of an azimuthally symmetric polarization artifact centered on the source, resulting from a combination of beam, detector and source properties. The simulation approximately reproduces the observed ring structure surrounding Cas A in Figure 19, but is brighter by ~35%, and does not include details such as the asymmetric scan-angle distribution in the data.

Figure 21. Position angle of integrated polarization of Tau A in equatorial coordinates as a function of wavelength squared. The WMAP results from Table 15 are shown in red, with error bars that include a systematic uncertainty of 1.5. Results shown in black are from references in Wilson (1972) and from Aumont et al. (2010) at 90 GHz for a 10 arcmin beam. The linear fit gives an intrinsic polarization position angle of 148 ± 0.3 and a rotation measure of −24.1 ± 0.2 rad m⁻².

3C274. The WMAP K-band flux agrees with that of Janssen et al. (1974) at 22.29 GHz. The combined data are better fit by a quadratic ($\chi^2 = 0.99$) than by a linear power law ($\chi^2 = 2.54$). Curvature in the overall spectrum might be expected since 3C274 has a steep spectrum halo. Above 10 GHz, the contribution of the halo to the total flux is <1% (Baars et al. 1977). Over the WMAP frequency range, the quadratic fit and the WMAP only power-law fit are not significantly different. The data of Ott et al. (1994) give a flatter 1.4–10.6 GHz spectral index than that of Baars et al. (1977), and they suggested that this may be due to core activity that could cause variability at the 5–10% level. As noted above, variability of about 4% and 17% has been observed at 43 GHz and 90 GHz, respectively.

5. CONCLUSIONS

WMAP data provide well-calibrated radiometry of the outer planets and bright sources. The seven-year data provide the longest WMAP baseline to date from which to study temporal variability, plus an increase in signal-to-noise which allows us to include fainter objects such as Uranus and Neptune in the analysis.

Jupiter temperatures derived from the seven-year data are within 1σ of the previously published five-year values of Hill et al. (2009). The disk-integrated temperatures derived for Jupiter at WMAP frequencies have uncertainties of less than 1%, with an apparent seasonal stability of $\Delta T/T = 0.2\% \pm 0.4\%$. As a planet, Jupiter has additional advantages in that it has a small apparent angular diameter and moves with respect to the fixed sky, allowing for well-characterized background subtraction. Of the ten objects studied, WMAP uncertainties for Jupiter are lowest, and we continue to recommend it as the best means for transferring the WMAP dipole calibration to another microwave instrument.

With the aid of models to predict geometrical and/or intrinsic variations, the WMAP-derived temperatures for Mars and Saturn are predictable to $\lesssim 3\%$. The recommendation for using the Mars values needs to be tempered by the knowledge that these have been derived using mean seasonal properties only. The Saturn model is purely empirical, and can be improved with the addition of the 2009 and 2010 WMAP observations when the rings are nearly edge-on.

Uncertainties in the seven-year mean Uranus temperatures range from 3% at the W band to about 7% in the K and Ka bands; only the Q, V, and W measurements are suitable for calibration at the $\lesssim 5\%$ level. Some form of simple model including polar brightness effects would be required to extend the seven-year mean data here beyond the observing epoch, since long-term studies in the literature show clear seasonal temperature variations. There is also the surprising hint of a dip in the microwave spectrum near 30 GHz, where none is expected based on discussions in the literature.

Seven-year mean temperature uncertainties for Neptune exceed 5% at all WMAP frequencies and so are not recommended for serious calibration usage.

Flux densities in Stokes $I$ for the five celestial calibrators have typical uncertainties of 1%–3%, and are in good agreement with previous measurements in the WMAP frequency range. For four of the sources, the WMAP data and other available data are consistent with a simple well-defined spectrum over two decades in frequency or more. The WMAP observations improve the accuracy of the spectral fit parameters and in some cases they extend the frequency range where the object may be used for calibration. The uncertainties in the spectral fits are typically 1% or less in amplitude and 0.02 or less in spectral index. We provide new estimates for the secular variation of Cas A and Tau A, and provide limits and an estimate for year-to-year variability of the other sources. We present WMAP polarization data with uncertainties of a few percent for Tau A.

The seven-year WMAP data products are available to the research community through the Legacy Archive for Microwave Background Data Analysis (LAMBDA) at http://lambda.gsfc.nasa.gov.

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