Spectral and Temporal Monitoring of the Isolated Neutron Star RX J1308.6+2127 with *XMM-Newton*

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Abstract

The isolated neutron star (INS), RX J1308.6+2127, has been observed with *Chandra* and *XMM-Newton* several times between 2000 and 2007. The six most recent *XMM-Newton* observations are part of a monitoring campaign we initiated to study the long-term temporal and spectral properties of INSs. The primary goal of this investigation is to better quantify the similarities and differences between INSs and magnetar candidates (i.e., Anomalous X-ray Pulsars and Soft Gamma Repeaters) in terms of their spectral and temporal variability. Here, we present our analysis of the current data set and show that (i) the energy spectrum is well modeled by a blackbody with two absorption lines; (ii) the spectral parameters do not show significant time variability over the last 7 years; (iii) the pulse-profile is strongly energy-dependent, but stationary; and (iv) the pulse-frequency evolution is consistent with monotonic spin-down. Our spectral and temporal results are consistent with earlier analyses by Schwope et al. (2005, 2007) and Kaplan and van Kerkwijk (2005, KK05 hereafter), respectively. The inclusion of the new monitoring data provides more precise constraints on both spectral and temporal parameters of this INS. For INSs whose X-ray emission is not powered by spin-down (INSs, AXPs, and SGRs), RX J1308.6+2127 is among the most stable members. Spectral analysis supports the existence of two absorption lines in the spectrum, and nearly harmonic spectral features that vary with the rotational phase of the star. Additional study of the spectral features may constrain theories concerning the local environment of INSs.

Conclusions

- RX J1308.6+2127 exhibits temporal and spectral stability over the time period of 2000-2007, unlike the INS RX J0720.4-3125.
- The pulse profile for RX J1308.6+2127 is strongly energy-dependent, but stationary.
- The energy spectrum is well modeled by an absorbed blackbody and two absorption lines.
- Phase-resolved spectroscopy indicates that the absorption-line energies vary in phase with one another at nearly harmonic energies.

Observations and Models

Table 1: Observations of RX J1308.8+2127 with *XMM-Newton* and *Chandra*

Obs	Date	MJD[a]	Telescope	Obsid	Exposure[b] (ksec)	Data Mode	Grating
1	2001-12-31	52274.25	*XMM-Newton*	0090010101	9.6	EPIC PN	RGS[c]
2	2003-01-01	52640.43	*XMM-Newton*	0157360101	24.2	EPIC PN	RGS
3	2003-12-30	53003.47	*XMM-Newton*	0163560101	27.0	EPIC PN	RGS
4	2005-06-25	53546.11	*XMM-Newton*	0305900201	12.3	EPIC PN	RGS
5	2005-06-27	53548.09	*XMM-Newton*	0305900301	11.6	EPIC PN	RGS
6	2005-07-15	53566.42	*XMM-Newton*	0305900401	11.0	EPIC PN	RGS
7	2006-01-10	53745.88	*XMM-Newton*	0305900601	13.3	EPIC PN	RGS
8	2006-06-08	53894.98	*XMM-Newton*	0402850301	4.6	EPIC PN	RGS
9	2006-06-16	53902.95	*XMM-Newton*	0402850401	5.7	EPIC PN	RGS
10	2006-06-27	53913.19	*XMM-Newton*	0402850501	9.5	EPIC PN	RGS
11	2006-07-05	53921.29	*XMM-Newton*	0402850901	6.4	EPIC PN	RGS
12	2006-12-27	54096.68	*XMM-Newton*	0402850701	7.6	EPIC PN	RGS
13	2007-06-11	54262.65	*XMM-Newton*	0402851001	7.9	EPIC PN	RGS
[d]	2000-06-24	51719.51	*Chandra*	731	10.3	ACIS-S	None
[e]	2002-05-21	52415.19	*Chandra*	2790	19.5	ACIS-I	None
[d]	2004-03-30	53095.36	*Chandra*	4595	90.8	HRC-S	LETG [f]
14	2005-02-14	53415.68	*Chandra*	5522	15.9	ACIS-S	None
15	2005-02-15	53416.59	*Chandra*	5523	5.7	ACIS-S	None
16	2005-02-19	53420.17	*Chandra*	5524	5.1	ACIS-S	None
17	2005-03-10	53439.03	*Chandra*	5525	5.6	ACIS-S	None
18	2005-07-09	53560.26	*Chandra*	5526	15.1	ACIS-S	None
19	2005-07-10	53561.25	*Chandra*	5527	5.0	ACIS-S	None
20	2005-07-14	53565.76	*Chandra*	5528	5.2	ACIS-S	None
21	2005-07-29	53580.78	*Chandra*	5529	5.2	ACIS-S	None

[a] MJD reported represents the center for each epoch.
[b] Exposure time remaining after GTI filter was applied
[c] Reflection Grating Spectrometer
[d] *Chandra* observations 731 and 4595 were included in temporal analysis only.
[e] This observation was not included in our analysis due to pulse pile-up and insufficient temporal resolution.
[f] Low Energy Transmission Grating

Table 2: Spectral Models for RX J1308.6+2127

Model 1: (Figures 3 and 7)

- XSPEC model definition: wabs(bbody + Gaussian + Gaussian)
- Free parameters: blackbody temperature and normalization
- Constrained parameters: column density, line energies, sigmas, and normalizations

Model 2: (Figures 4 and 8)

- XSPEC model definition: wabs(bbody + Gaussian + Gaussian)
- Free parameters: line energies and normalizations
- Constrained parameters: column density, black body temperature and normalization, and line sigmas

"Free parameter" - allowed to vary independently for each observation
"Constrained parameter" - linked for all observations to a single adjustable value

RXJ1308 was observed with *XMM-Newton* and *Chandra* 24 times between 2000 and 2007 (Table 1). Data were analyzed both temporally and spectrally. Spectral models (Table 2) were similar to those presented by Schwope et al. (2007).

Temporal Analysis

Data from *XMM-Newton* and *Chandra* were filtered to remove drop-outs and flares, then barycenter corrected using the source position α = 13h08m48.27" δ = +21º27'06.8" (KK05). Phase-coherent timing analysis was performed using the same technique used in the timing of other pulsars (Woods et al. 2004). The phase residuals are well fit by a quadratic (Figure 1) and the resulting spin parameters (Table 3) were found to be consistent with the KK05 ephemeris, although of somewhat higher precision.

The data for each observing epoch were folded according to the new timing solution to investigate the pulse-profile evolution. As shown in Figure 2, little variability was seen over this time span.

Table 3: RX J1308.6+2127 Pulse Ephemeris

Parameter	Value
Epoch……………………………………..	53400.0000 MJD TDB
Spin frequency, ν ………………………..	0.096969491004(27)[++] Hz
Spin frequency derivative, $\dot{\nu}$ …………….	-1.05233(69) Hz/s
Inferred magnetic field strength, B ……..	3.5×10^{13} G
Inferred age, τ …………………………..	1.5×10^{6} yr

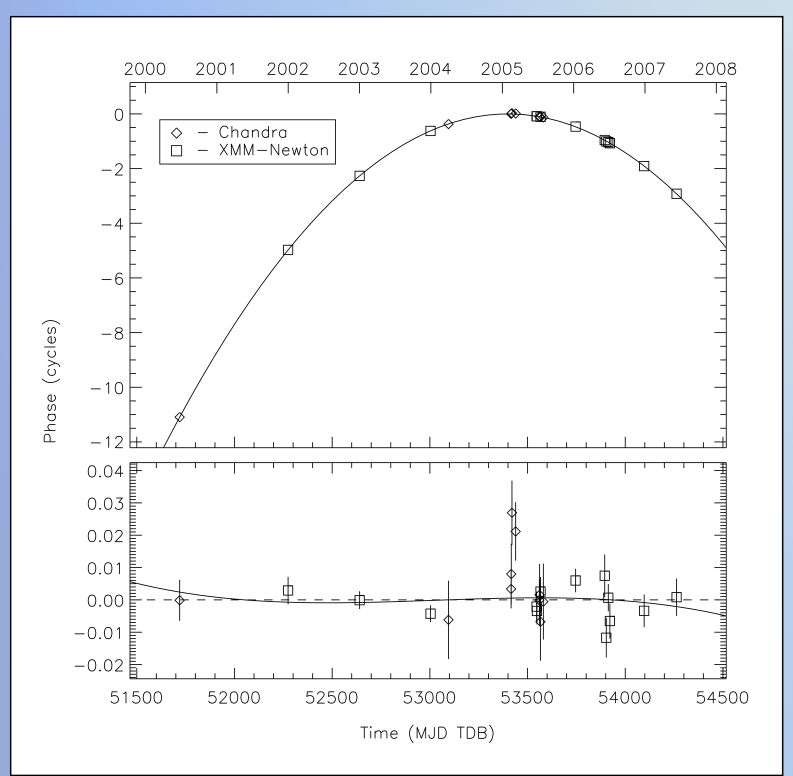

Figure 1

Pulse-ephemeris residuals for RXJ1308. The top panel shows residuals minus a linear fit. The bottom panel shows residuals minus a quadratic fit. The solid line in the bottom panel represents a cubic fit to the residual. The cubic term did not significantly improve the fit.

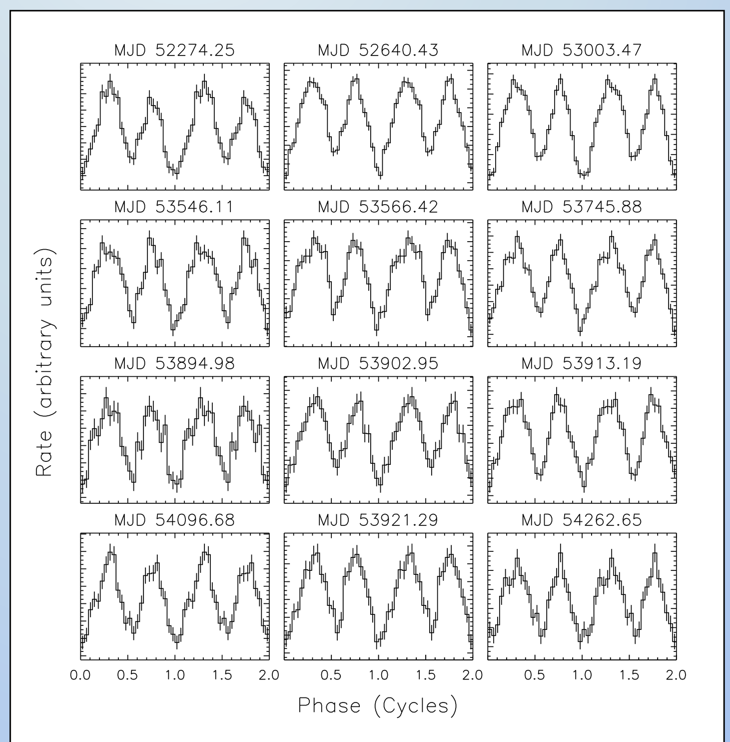

Figure 2

Pulse morphology for RXJ1308. Two full periods are shown for each epoch for energies from 0.2 to 1.4 keV. The double-peaked profile is a known characteristic of the source (Haberl et al. 2003). No significant variation is seen in the pulse profile over time.

Spectral Analysis

The *XMM-Newton* data were further processed for spectral analysis. *Chandra* data were excluded to avoid inter-instrumental calibration uncertainties. The spectral models applied are shown in Table 2. These were based on the general model of a blackbody with two absorption lines, proposed by Schwope et al. (2007). The models differed from one another concerning which parameters were allowed to vary. Either the blackbody parameters or the line parameters varied independently for each observation, while the others remained fixed to the same adjustable value. Phase-average spectroscopy (Figures 3 and 4) indicated that the source is spectrally stable. No significant variability was observed over this time span.

Data were then folded according to the timing solution in Table 3. The pulse profile was plotted for each of 12 energy bands, ranging from 0.18 to 4.00 keV (Figure 5). The profile was found to be strongly energy-dependent.

Next, phase-resolved spectroscopy was performed. The source was first modeled as a simple absorbed blackbody. The residuals in the spectrum (Figure 6) affirmed the presence of absorption features between 0.2 and 0.6 keV and between 0.6 and 1.5 keV.

Models 1 and 2 were applied to the phase-resolved data, seeding the positions of the absorption lines with the values observed in Figure 6. The parameters were found to vary with the rotational phase of the star (Figures 7 and 8).

The ratio of the energies for the absorption lines in Model 2 (Figure 8) was nearly constant with a value of ~2. This suggests that the absorption lines may be harmonic. Possible explanations include proton cyclotron radiation in a magnetic field of ~10^{14} G, or bound-bound transitions in a Hydrogen atmosphere (Zane et al. 2005, Ho & Lai 2004).

Phase-Averaged Spectroscopy

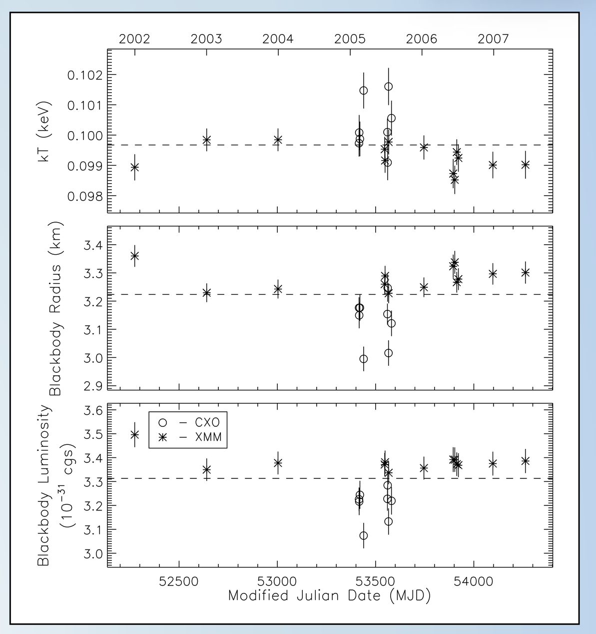

Figure 3

Spectral history for RXJ1308, phase-averaged spectroscopy. Figures 3 and 4 represent Models 1 and 2, respectively (see Table 2). No significant variability was observed between 2000 and 2007.

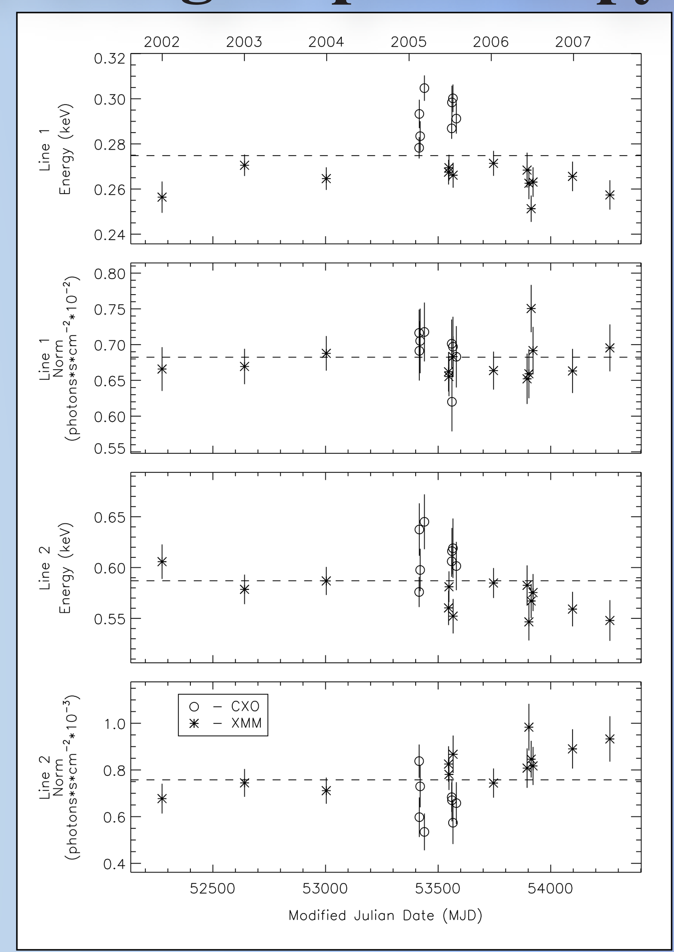

Figure 4
(caption to left)

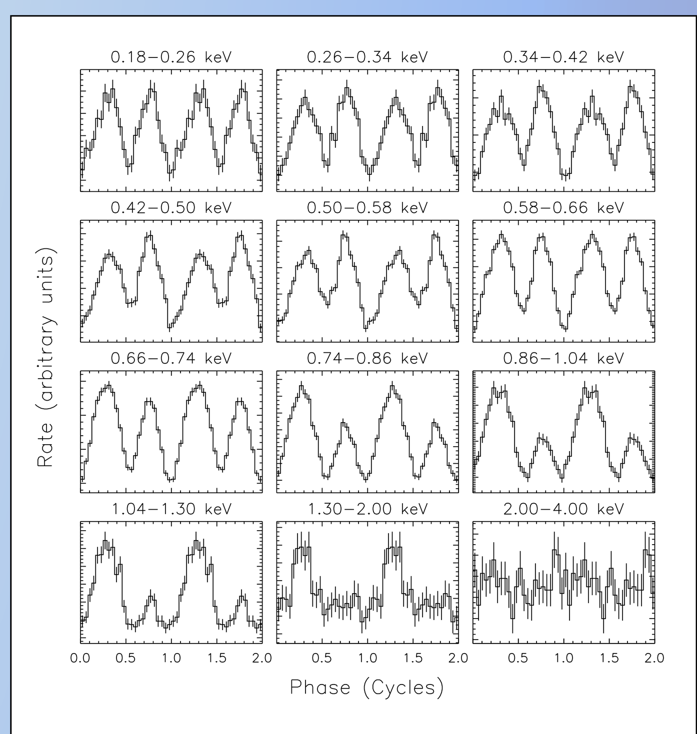

Figure 5

Pulse profile versus energy for RXJ1308. The variation in pulse height indicates that the pulse profile is strongly energy-dependent.

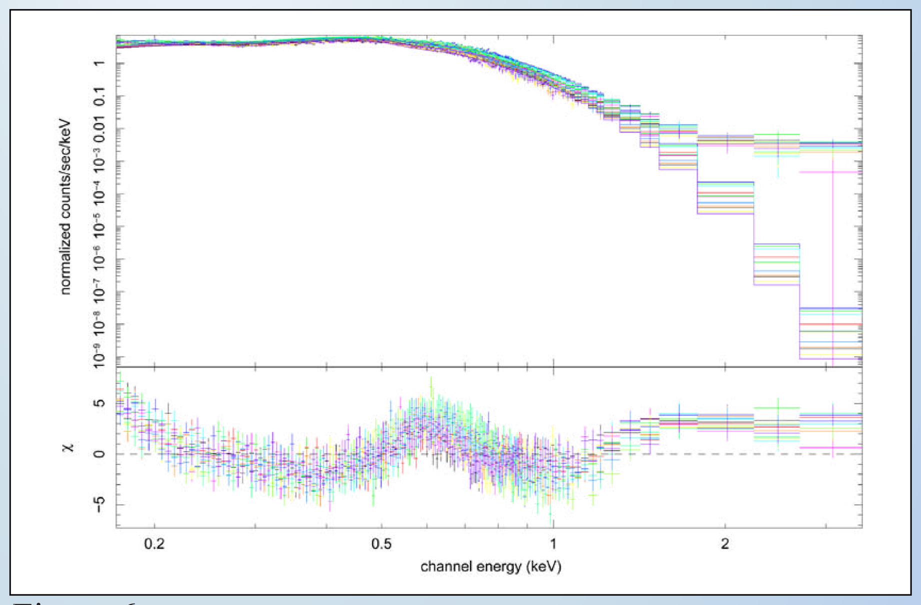

Figure 6

Spectrum of RXJ1308 and the residuals when the source is modeled as an absorbed blackbody. Trends in the residual indicate absorption features between 0.2 and 0.6 keV and between 0.6 and 1.5 keV.

Phase-Resolved Spectroscopy

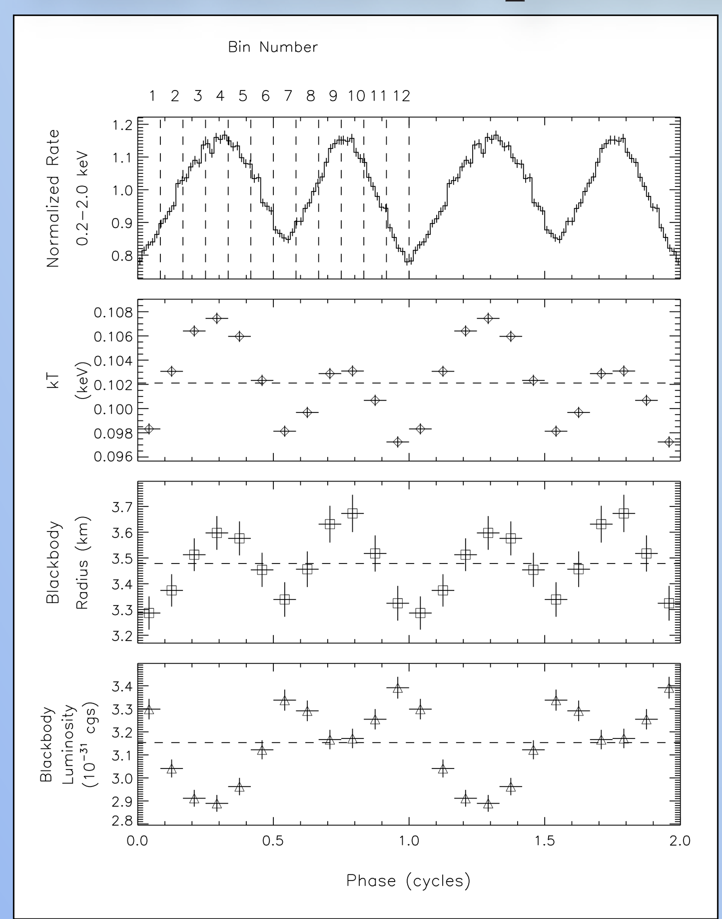

Figure 7

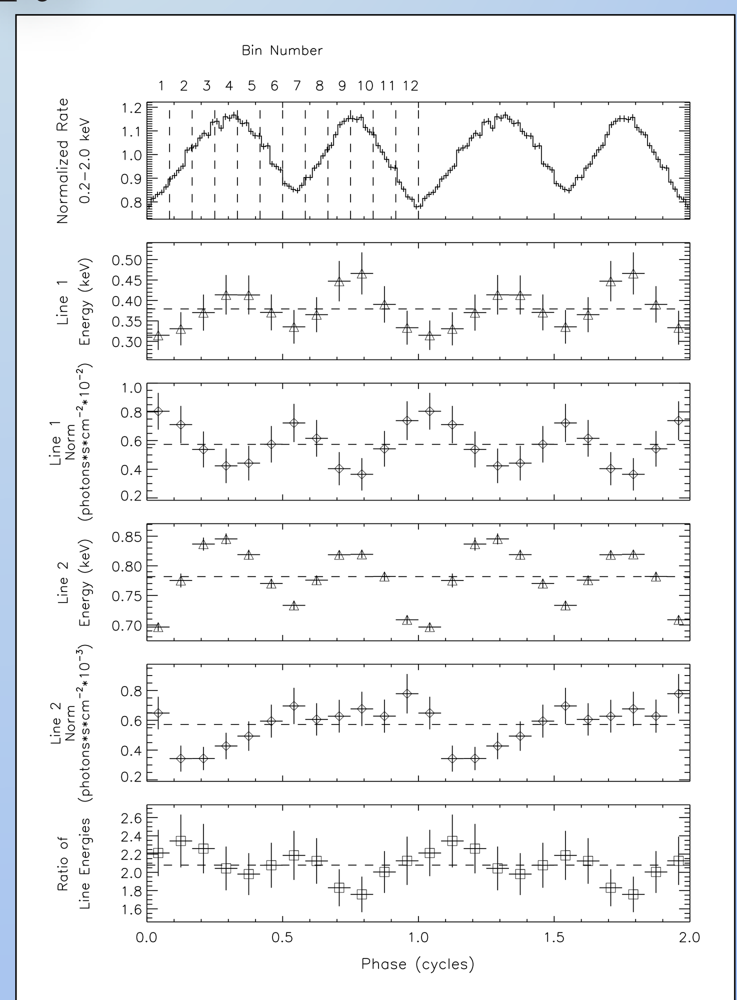

Figure 8

Phase-resolved spectroscropy for RXJ1308. Figures 7 and 8 represent Models 1 and 2, respectively (see Table 2). Spectral parameters are found to vary with the rotational phase of the star. The absorption-line energies in Figure 8 appear to be harmonics, with a ratio of ~ 2 (bottom panel).

References

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[++] Numbers in parentheses represent the 1σ error in the two least significant digits of the value reported.

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