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UPPER LIMITS ON TeV GAMMA-RAY EMISSION FROM CENTAURUS A, VELA X-1, CENTAURUS X-3, AND CIRCINUS X-1

W. H. ALLEN,[1] I. A. BOND,[2,3] E. BUDDING,[1] M. J. CONWAY,[2] A. DANIEL,[2] K. B. FENTON,[4] H. FUJII,[5] Z. FUJII,[6] N. HAYASHIDA,[7] K. HIBINO,[7] M. HONDA,[7] J. E. HUMBLE,[4] S. KABE,[5] K. KASAHARA,[8] T. KIFUNE,[7] G. D. LYTHE,[2] A. MASAIKE,[9] Y. MATSUBARA,[6] K. MITSUI,[7] Y. MIURA,[5] M. MORI,[5] Y. MURAKI,[6] M. NAGANO,[7] T. NAKAMURA,[9] M. NISHIZAWA,[10] P. M. NORRIS,[2] S. OGIO,[11] TO. SAITO,[7] M. SAKATA,[10] H. SATO,[7] H. M. SHIMIZU,[5] M. SPENCER,[2] J. R. STOREY,[2] T. TANIMORI,[11] M. TESHIMA,[7] S. TORII,[8] A. WADSWORTH,[1] Y. WATASE,[5] M. D. WOODHAMS,[2] Y. YAMAMOTO,[10] P. C. M. YOCK,[2] AND T. YUDA[7]
(THE JANZOS COLLABORATION)

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ABSTRACT

The active galaxy Centaurus A and the X-ray binary systems Vela X-1, Centaurus X-3, and Circinus X-1 were monitored for VHE gamma-ray emission above 1 TeV with the JANZOS Cerenkov facility during 1988 and 1989. No evidence was found for persistent or episodic emission from any of these objects. Subseqeunt upper limits on the integral fluxes of 2.2×10^{-11}, 2.8×10^{-11}, 4.0×10^{-11}, and 4.2×10^{-11} cm^{-2} s^{-1}, respectively, were obtained for these objects. These limits are consistent with results of observations made by other groups.

Subject headings: galaxies: individual (Centaurus A) — gamma rays: observations — stars: individual (Vela X-1, Centaurus X-3, Circinus X-1) — X-rays: galaxies — X-rays: stars

1. INTRODUCTION

At a distance of ~ 5 Mpc, Centaurus A is the closest galaxy. Evidence of VHE gamma-ray emission from Cen A was reported by a Harvard-Sydney group which operated a Cerenkov telescope at Narrabri from 1972 to 1974 (Grindlay et al. 1975). Recent observations from the Durham group show no evidence of VHE emission (Carraminana et al. 1990). Data obtained at the Buckland Park air shower array operated by the Adelaide group between 1979 and 1981 show marginal evidence for UHE gamma-ray emission above 10^{15} eV (Clay, Gerhardy, & Liebing 1984). Data collected between 1984 and 1989 at this facility also showed some evidence for UHE emission from this object (Bird & Clay 1990).

Vela X-1 is a 283 s X-ray pulsar in a 8.97 day binary orbit. At a distance of 1.4 kpc this is the closest object identified as a possible VHE and UHE gamma-ray source. The first detection at these energies was made by the Adelaide group where Vela X-1 was reported to emit gamma rays above 3 PeV specifically at orbital phase 0.63 (Protheroe, Clay, & Gerhardy 1984). Subsequently, the Potchefstroom group reported UHE emission at orbital phase 0.13 (van de Walt 1987) while the BASJE group at Chacaltaya reported emission at orbital phase 0.5 (Suga 1987). At TeV energies, evidence of pulsed emission at the X-ray period was first reported by the Potchefstroom group (North et al. 1987). This detection was confirmed in later observations by the same group (Raubenheimer et al. 1989) and also by the Durham group (Carraminana et al. 1989). Recent observations at TeV energies obtained by experiments at White Cliffs (Clay et al. 1987) and Woomera (Thornton et al. 1991) do not confirm these detections. The early positive detections at PeV energies are also not confirmed by recent observations by SPASE (Finnemore et al. 1991), the JANZOS air shower array (Bond et al. 1990), and SUGAR (Meyhandan 1992).

Cen X-3 is a 4.8 s X-ray pulsar in a 2.1 day binary orbit. The Durham and Potchefstroom groups have independently reported evidence for pulsed emission of VHE gamma rays occurring in the orbital phase range 0.7–0.8 (North et al. 1990; Brazier et al. 1990). Cir X-1 is an X-ray binary with a possible orbital period of 16.5 days but no pulsar activity has been detected. No positive detections of DC or pulsed VHE gamma-ray emission have been reported for this object. An upper limit on the UHE flux obtained by the Buckland Park air shower array was given by the Adelaide group (Protheroe & Clay 1985) and recently an upper limit on the VHE flux was reported by the Durham group (Bowden et al. 1991).

In our previous paper (Allen et al. 1992, hereafter Paper I), we reported observations of various objects in the Magellanic Clouds employing the Cerenkov technique at large zenith angles using the JANZOS facility. Here we present results of VHE observations of Cen A, Vela X-1, Cen X-3, and Cir X-1 obtained at conventional zenith angles less than 30°. We find no evidence for persistent or episodic emission from any of these objects. The subsequent upper limits are compared with the previous results described above in order to gain a per-

[1] Carter National Observatory of New Zealand, Wellington, New Zealand.
[2] Department of Physics, University of Auckland, Auckland, New Zealand.
[3] Present address: Institute of Physical and Chemical Research, Wako, 351-01, Japan.
[4] Department of Physics, University of Tasmania, Hobart 7001, Australia.
[5] National Laboratory for High-Energy Physics (KEK), Tsukuba 305, Japan.
[6] Cosmic Ray Section, STE Laboratory, Nagoya University, Nagoya 464, Japan.
[7] Institute for Cosmic Ray Research, University of Tokyo, Tokyo 188, Japan.
[8] Department of physics, Kanagawa University, Yokohama 221, Japan
[9] Department of Physics, Kyoto University, Kyoto 606, Japan
[10] Department of Physics, Konan University, Kobe 658, Japan.
[11] Department of Physics, Tokyo Institute of Technology, Tokyo 152, Japan.

TABLE 1

SUMMARY OF OBSERVATIONS OF CENTAURUS A, VELA X-1, CENTAURUS X-3 AND CIRCINUS X-1

Target Object	R.A.	Declination	Observational Period	Number of Nights	Effective Hours Data
Cen A	201°2	−43°0	1988/4/11–4/16	5	9.3
			1989/3/6 –6/6	31	47.6
Vela X-1	135.4	−40.6	1988/1/21–4/16	13	22.1
			1989/3/2 –4/12	15	22.7
Cen X-3	170.2	−60.6	1988/4/17–4/22	5	13.5
Cir X-1	229.5	−57.1	1988/4/17–4/23	5	14.9

spective of the current status regarding VHE and UHE observations.

2. EXPERIMENT, OBSERVATIONS, AND ANALYSIS

The JANZOS Cerenkov telescope is described in detail in Paper I. Briefly it comprises three mirrors which operate in the drift scan mode and uses fast timing for arrival direction determination. Cerenkov light emitted by an air shower is identified by three-fold coincidences among phototubes from each mirror viewing the same direction. Initially each telescope had 10 photomultiplier tubes arranged in a single row on the focal plane. In 1988 November 18, more phototubes were added to each telescope giving a total of three rows. The phototubes in the outer rows were not used for triggering in these observations. However, all phototubes are interrogated for pulse height and timing information during an event trigger.

Cen A, Vela X-1, Cen X-3, and Cir X-1 were observed during 1988 and 1989 as summarized in Table 1. The effective hours data shown in Table 1 is the net exposure allowing for instrumental dead time. The relative positions of Cen A and Vela X-1 allowed both objects to be observed on some nights. This was also the case for Cen X-3 and Cir X-1. The total transit time across the field of view was 2 hr for Cen A and Vela X-1, 3.2 hr for Cir X-1, and 3.5 hr for Cen X-3. The observations were all carried out at zenith angles less than 30°.

The energy threshold and effective area for these observations were calculated using the method described in Paper I. The energy threshold was found to be insensitive to zenith angles less than 30°. The threshold energy is thus taken to be 1 TeV, being the value corresponding to observations at vertical zenith angles. The effective area of the detector was estimated to be 1.0×10^8 cm^2 for the observations of Cen A and Vela X-1 and 1.4×10^8 cm^2 for those of Cen X-3 and Cir X-1.

The primary arrival direction of each event is calculated by fitting a unique plane to the times recorded by the three mirrors. For those events where multiple hits are recorded in a mirror, the time is taken from the signal of maximum amplitude as was also the case for the large zenith angle observations described in Paper I. Also as described in Paper I, measurements of the pointing direction of each phototube obtained from the observation of bright star transits were used to check for systematic errors in the calibration of instrumental timing delays. Figure 1 shows the distribution of reconstructed arrival directions of Cerenkov events recorded during one night of observations of Vela X-1 on 1988 March 23.

The angular resolution was determined by estimating the effects of shower front curvature and diffuseness as described in Paper I. From simulations of vertically injected gamma initiated showers (Lythe 1990), the curvature may be expressed as 1.2 ns per 100 m of lateral distance from the core. The diffuseness of the shower front was estimated by looking at the distribution of time differences between adjacent phototubes for multiple hit events. The HWHM diffuseness error was found to be ± 1.8 ns. Combining these effects, the angular resolution is estimated to be $\pm 0°5$ in both right ascension and declination. For these observations, zenith angle effects are small and may be neglected.

3. RESULTS

3.1. *DC Emission*

For each source a 1° wide declination strip centered on the source was divided into nonoverlapping R.A. bins and the observed and background events were then distributed into these bins. The background as a function of right ascension was calculated using the method described in Paper I. The R.A. bin width was 1°2 for Cen A and Vela X-1 and 2° for Cen X-3 and Cir X-1. The results of the R.A. scans corresponding to the total data set of observations of Vela X-1 are shown in Figure 2. The roughly symmetric feature of the distribution is a geometric effect characteristic of the drift scan mode of operation. Those regions of the sky with right ascensions around the peak have the greatest exposure in which they are observed by all 10 phototubes from each telescope.

The R.A. bins centered on each source were then examined for excess events over the background. None of these sources show significant excess events from their respective total data sets. Upper limits at the 95% confidence level on the number of excess events were then calculated using the following expression (described in Paper I)

$$N_{95} = \frac{1}{f}\left(N_T - N_B + 1.9\sqrt{N_T + \frac{N_B^2}{N}}\right),$$

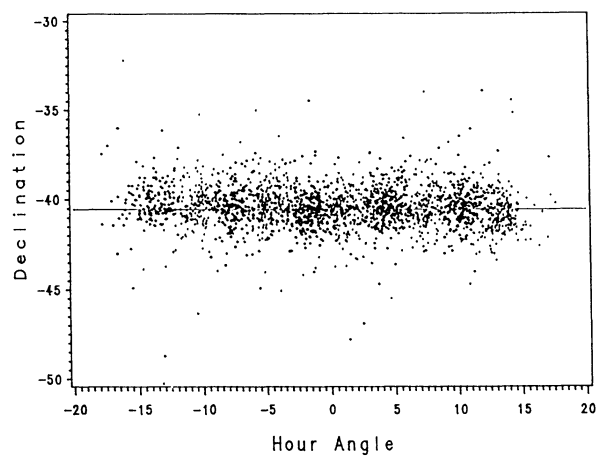

FIG. 1.—Distribution in hour angle and declination of arrival directions of analyzed events corresponding to one night of observation of Vela X-1.

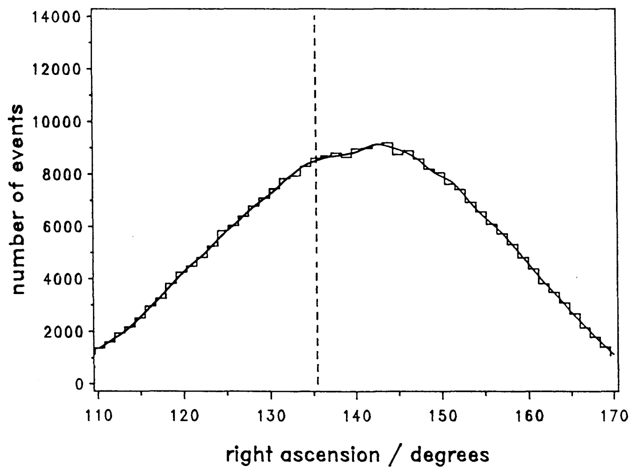

FIG. 2.—Results of a right ascension scan across the declination strip centered on Vela X-1 from the total data set of observations made during 1988 and 1989.

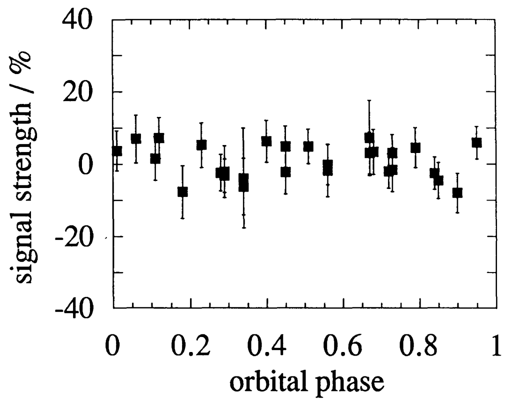

FIG. 3.—Signal strengths of excess events from the direction of Vela X-1 plotted as a function of orbital phase observed on each night.

where f is the fraction of events expected to fall within the bin region given the angular resolution for gamma-ray events, N_T and N_B are the number of observed and background events in the source bin, and N is the total number of events in the declination strip. The term under the radical sign is the quadrature sum of the errors in the observed and background event numbers. The factor 1.9 corresponds to the 95% confidence level (1.9 σ). The observed and background event numbers are given in Table 2 along with the corresponding upper limits, at the 95% confidence level, on the number of excess events and the VHE fluxes.

3.2. *Episodic Emission*

Observations over different nights were compared using the signal strength given by

$$S = \frac{N_T - N_B}{N_B} \times 100\% .$$

This quantity was calculated for each night of observations of Cen A, Vela X-1, Cen X-3, and Cir X-1. There are no strong signal strengths seen on any observation night for any object. The observed signal strengths are all consistent with statistical fluctuations.

Each two hour observation of Vela X-1 on a given night samples about 1% of the 8.97 day binary orbit. The observed signal strengths as a function of orbital phase (calculated using the ephemeris of Deeter et al. 1987) are shown in Figure 3. None of the individual signal strengths show a significant positive excess. The sampled orbital phases are scattered fairly evenly throughout the full range of 0–1. Thus if Vela X-1 is steadily emitting VHE gamma rays at a flux detectable with this experiment, then it must be doing so over a narrow orbital phase range with a width less than 0.1. These results are also consistent with the observations of the Durham group which indicated that the Vela X-1 was not emitting VHE gamma rays at any preferred orbital phase.

The limited data on Cen X-3 precludes a detailed comparison with the Durham and Potchefstroom results regarding the TeV emission between orbital phases 0.7 to 0.8. However, we observed Cen X-3 between phases 0.77–0.84 on 1988 April 18 and between 0.68–0.75 on 1988 April 22. Neither of these nights showed positive excesses.

TABLE 2

95% UPPER LIMITS ON VHE FLUXES ABOVE 1 TeV FOR CENTAURUS A, VELA X-1 CENTAURUS X-3, AND CIRCINUS X-1

Object	N_T	N_B	N_{95}	Integral Flux Upper Limit (10^{-11} cm^{-2} s^{-1})
Cen A	11000	10955 ± 19	426	2.2
Vela X-1	8600	8513 ± 17	458	2.8
Cen X-3	3004	2999 ± 16	195	4.0
Cir X-1	3874	3864 ± 12	225	4.2

3.3. *Pulsed Emission*

A pulsar periodicity search using the Rayleigh test was carried out on each of the following subsets of the Vela X-1 data base: (1) 1988 January 1–March 25, (2) 1988 April 11–16, (3) 1989 March 2–April 12. The observations of 1988 are divided into two because a power failure to the clock on April 10 resulted in a loss of timing coherency. The 1989 observations were analyzed separately because of the large gap in the data from 1988 to 1989. For each subset a periodicity search was carried out in the range 282.7–283.3 s with a test period spacing of 0.02 s. All event times were corrected to the Solar System Barycentre with a further correction to the focus of the binary orbit of Vela X-1 using the elements of Nagase et al. (1984). No significant Rayleigh power at any test period was found which could not be attributed to being statistical in origin. A similar periodicity search in the 4.820–4.826 s range was carried out on the Cen X-3 data base. Corrections to the binary orbit focus were carried out using the elements of Kelley et al. (1983). This analysis also did not show any nonstatistical effects. We thus do not find any evidence for pulsed VHE gamma-ray emission from Vela X-1 and Cen X-3 near their respective X-ray periods.

3.4. *Comparison with Results of Other Groups*

In Figure 4, our upper limit on the VHE gamma-ray flux from Cen A is compared with the early positive detection of Grindlay et al. (1975) and the recent null result from the Durham group (Caraminana et al. 1989). Also included is an upper limit on the UHE emission obtained by the JANZOS air shower array (Spencer 1990). Where appropriate, all upper limits are converted to their equivalent values at the 95% confidence levels.

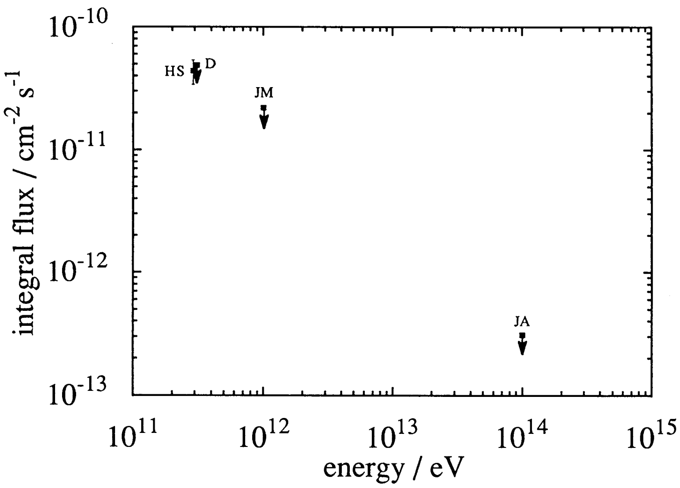

FIG. 4.—Comparison of upper limits on the VHE and UHE gamma-ray fluxes from Cen A. The present result obtained using the JANZOS Cerenkov mirror is designated as "JM." An upper limit from an analysis of the JANZOS air shower array data collected from 1987 October to 1989 April is designated as "JA." Results from the Harvard-Sydney and Durham experiments are designated as "HS" and "D," respectively.

In Figure 5 we compare our upper limit on the VHE gamma ray flux from Vela X-1 with results obtained by other groups. At the VHE level, these include the positive detections reported by the Durham group (Caraminana et al. 1989) and the Potchefstroom group (North et al. 1987; Raubenheimer et al. 1989) and upper limits obtained by the White Cliffs experiment (Clay et al. 1987) and the Woomera telescope (Thornton et al. 1991). At the UHE level, we include the detections reported by the Adelaide group (Protheroe et al. 1984), the Potchefstroom group (van der Walt et al. 1987), and the BASJE group (Suga 1987). Upper limits on the UHE flux obtained by the JANZOS experiment (Bond et al. 1990), SPASE (Finnemore et al. 1991), and SUGAR (Meyhandan et al. 1992) are also included. Among the VHE upper limits, our results is at present the most restrictive. Our upper limit is also not inconsistent with the positive results of the Durham and Potchefstroom groups.

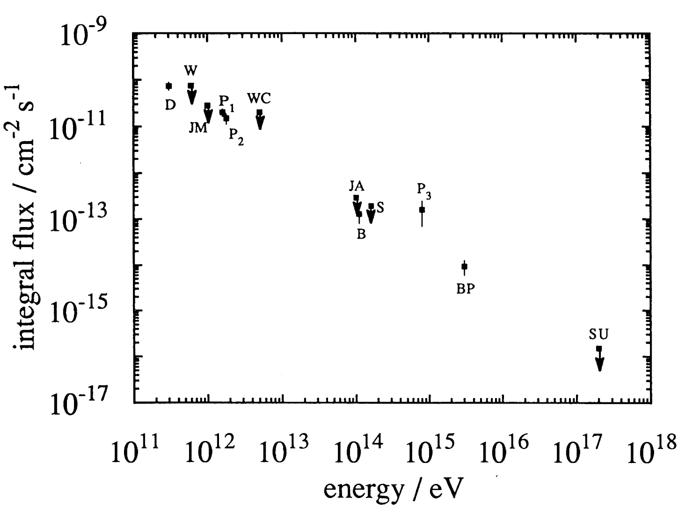

FIG. 5.—Comparison of upper limits on the VHE and UHE gamma-ray fluxes from Vela X-1. The present result obtained using the JANZOS Cerenkov mirror is designated as "JM." An upper limit from an analysis of the JANZOS air shower array data collected from 1987 October to 1989 April is designated as "JA." Results from other experiments are designated as follows: Durham, "D"; Woomera, "W"; and Potchefstroom, "P$_1$," "P$_2$," and "P$_3$"; White Cliffs, "WC"; BASJE, "B"; SPASE, "S"; Buckland Park, "BP"; and SUGAR, "SU."

4. DISCUSSION

The upper limits on the VHE fluxes may be used to constrain the gamma-ray luminosities of these sources. For an $E^{-2}dE$ spectrum with a cutoff at E_{max}, the upper limit on the integral flux above the threshold energy E_{th} implies a corresponding upper limit on the luminosity given by

$$L(>E_{th}) < 4\pi D^2 F(>E_{th}) \frac{E_{th} E_{max}}{E_{max} - E_{th}} \ln\left(\frac{E_{max}}{E_{th}}\right),$$

where D is the distance to the source. These limits are given in Table 3 for the observations of Cen A, Vela X-1, Cen X-3, and Cir X-1 and are compared with their X-ray luminosities. For Cen A we used the Compton-Synchrotron model of Grindlay (1975) which describes the observed spectrum from microwave through X-ray wavelengths up to the reported VHE flux. In the TeV region, this model predicts a power law with a differential index of -2 and a cutoff at 4 TeV. For the three X-ray binaries we used an $E^{-2}dE$ spectrum with a cutoff at 10^{17} eV.

The upper limit on the VHE gamma-ray luminosity of Cen A is 19 times greater than the X-ray luminosity. Given its distance and the fact that the X-ray luminosity of Cen A is relatively low among active galaxies, the nondetection at VHE energies reported here is perhaps not surprising. The recent detection of intense MeV gamma rays from 3C 279 by *EGRET* (Hartman et al. 1992) demonstrates the importance of continued studies of VHE and UHE gamma-ray emission from active galactic nuclei (AGNs). If the flux reported from 3C 279 above 100 MeV extends into the TeV region, this should be detectable with existing VHE facilities. Cen A is a particularly important object since it is the closest AGN.

Vela X-1 is the closest object in this sample, and naturally this object has the most stringent constraint on the VHE gamma-ray luminosity. However the X-ray luminosity of Vela X-1 is relatively low. Our observations yield an upper limit on the ratio of the VHE luminosity of 0.0020. The X-ray luminosity of Cir X-1 on the other hand is the highest among this sample of X-ray binaries. The corresponding luminosity ratio upper limit for this object is the smallest at 0.0011.

It is universally recognized that the biggest hindrance in the progress of VHE gamma-ray astronomy is the high proton-induced background. Regarding northern hemisphere sources, considerable progress has been made by the Whipple collaboration which discriminates proton- and gamma-ray–induced air showers on the basis of their Cerenkov images. The applica-

TABLE 3

95% UPPER LIMITS ON VHE LUMINOSITIES ABOVE 1 TeV FOR CENTAURUS A, VELA X-1, CENTAURUS X-3, AND CIRCINUS X-1

Object	Distance (kpc)	Luminosity Upper Limit (10^{35} ergs s^{-1})	L_X (10^{35} ergs s^{-1})
Cen A	5000	19×10^{5} [a]	10^5
Vela X-1	1.4	0.12 [b]	60
Cen X-3	10	8.5 [b]	800
Cir X-1	10	9.0 [b]	8000

[a] Based on $E^{-2}dE$ spectrum with cutoff at 4 TeV (Grindlay 1975).
[b] Based on $E^{-2}dE$ spectrum with cutoff at 10^{17} eV.

tion of this technique has resulted in a highly significant detection of VHE emission from the Crab pulsar (Weekes et al. 1989). An imaging telescope for the study of Southern Hemisphere sources is presently under development (CANGAROO, Hara 1990). The upper limits presented here provide a basis for subsequent observations with this facility whose results are naturally awaited with interest.

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