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AN EXTENDED SOFT X-RAY SOURCE IN DELPHINUS: H2027+19

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ABSTRACT

We report the detection of an extended (∼3°) source of soft X-ray emission, H2027+19, observed with the *HEAO 1* A-2 experiment. The object emits primarily in the 0.16–0.4 keV band, with a total flux in this band of $\sim 2 \times 10^{-11}$ ergs cm^{-2} s^{-1}. Although our data can be formally modeled with two discrete sources, a detailed analysis suggests that this alternative is not likely to be the case. We find that both simple continuum and coronal plasma models provide good fits to the observed pulse-height spectrum. The source parameters are restricted to $10^{5.8} < T < 10^{6.5}$ K, $N_x < 10^{21.3}$ cm^{-2} (Raymond and Smith plasma), and $10^{5.8} < T < 10^{7.0}$, $N_x < 10^{21.2}$ (exponential + Gaunt factor) at the 90% confidence level. The most likely physical models are either that the source is an old supernova remnant or that it is a region of enhanced soft X-ray emission surrounding an H I cloud imbedded in a coronal plasma, as suggested by Hayakawa *et al.* for the Lupus Loop.
Subject headings: nebulae: supernova remnants — X-rays: sources

I. INTRODUCTION

Recent *HEAO 1* results have included the detection of many new extended sources of soft X-ray emission. At least four of these have been identified as X-ray emitting supernova remnants (SNRs): PKS 1209−52, RCW 103 (Tuohy *et al.* 1979), MSH 11-54, and MSH 15-56 (Agrawal and Riegler 1979*b*), thus bringing the number of SNRs which emit in both the radio and X-ray regions to ∼16 (see, e.g., the review by Culhane 1977). Several of these newly discovered extended objects have no associated radio or optical counterpart (Agrawal and Riegler 1979*a;* Riegler, Agrawal, and Gull 1980). Hayakawa *et al.* (1979) have recently proposed that at least one extended soft X-ray source, the Lupus Loop (Palmieri *et al.* 1972; Seward *et al.* 1976; Winkler *et al.* 1979) may not be an old SNR, as commonly supposed. Instead, it may be a region of enhanced soft X-ray emission surrounding an H I cloud imbedded in an old SNR cavity (McKee and Cowie 1977; McKee and Ostriker 1977).

In this *Letter*, we report the discovery of a new extended soft X-ray source, and discuss various interpretations of its physical nature, including the old SNR and enhanced emission models described above.

II. OBSERVATIONS AND RESULTS

The data were obtained with one of the low-energy detectors (LED 1) on the *HEAO 1* A-2 experiment[4] (a detailed instrument description is given by Rothschild *et al.* 1979). The A-2 detectors scan the sky along great circles of ecliptic longitude; the LED 1 field of view used here is 1°.55 (scan direction) × 2°.95 FWHM, with a geometric collecting area of 177 cm^2.

To increase our sensitivity for the detection of new sources, we have superposed several days of scan data taken on 1977 November 6–8 near ecliptic latitude ∼40°. In Figure 1 we show the results of this procedure for the 0.16–0.4 keV band with an angular bin size of 0°.5. An extended region of emission is readily apparent: under a single extended source hypothesis the statistical significance of the feature is $>4\,\sigma$, even using the conservative procedure (Cash 1976) of jointly estimating the source position, strength, and extent. We point out that a model with two discrete point sources will formally fit the data. Analysis of individual day superpositions demonstrates, however, that both sources in such a model would have to possess similar spectra, have approximately the same intensity, and be located at the same ecliptic longitude. No evidence is found for day-to-day source variability. Although a dual source model is not conclusively ruled out, we find the combination of the above circumstances to be very unlikely, and therefore suggest that this new source, which we designate H2027+19, is of finite angular extent.

On this assumption, we estimate a source extent of 2°.8 ± 0°.7 along the scan direction, centered on the position $\alpha = 306°.8$, $\delta = 19°.5$ (1950). The corners of the 90% confidence error box for the centroid of position only are given by α, δ = (308.2, 19.7; 307.9, 20.3; 305.3, 19.5; 305.5, 18.9). Perpendicular to the scan direction the source is ∼3°–5° in extent, but this is harder to estimate because of the larger field of view (∼3°) and limited sampling.

We have fitted the pulse-height spectrum (corrected for adjacent sky background) of H2027+19 to simple continuum and Raymond and Smith (1977, 1980, hereafter RS) coronal plasma models. Since, for reasons outlined in § III, the source is likely to be a thermal emitter, we will omit any discussion of power-law models except to state that the acceptable range of

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parameter values includes $-4 < \alpha < -1$, $N_x < 10^{21}$ cm^{-2}, where α is the photon spectral index and N_x is the equivalent hydrogen column density derived using the Brown and Gould (1970) interstellar medium cross sections. Figure 2 shows the best-fit RS spectrum for H2027+19, while the inset shows the 90% confidence contours (Lampton *et al.* 1976; Cash 1976) for the parameters.

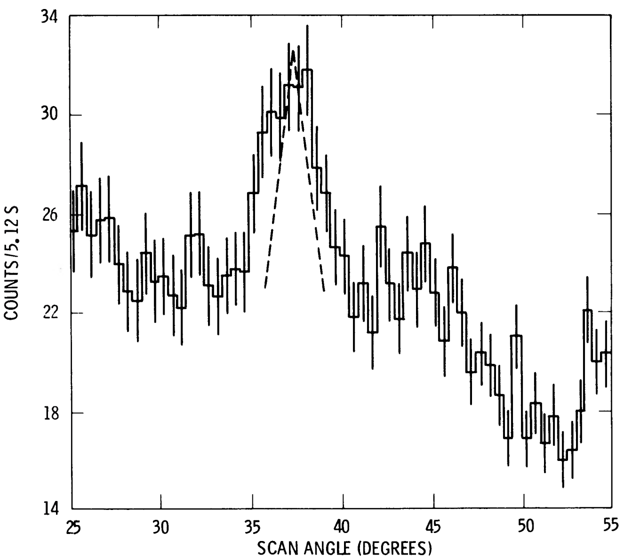

FIG. 1.—Count rate versus scan angle histogram for H2027+19 using data from 1977 November 6–8 in the 0.16–0.4 keV band of the *HEAO 1* LEDs. The collimator response function for a point source is indicated by the dashed triangle.

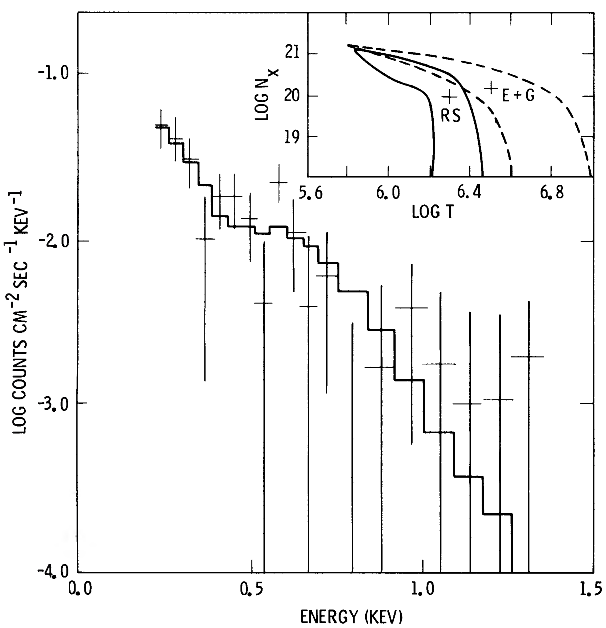

FIG. 2.—Best-fit X-ray pulse-height spectrum ($T = 10^{6.35}$, $N_x = 10^{20.0}$; RS plasma) for H2027+19. Inset: 90% confidence contours for the allowed parameters using both RS plasma and exponential + Gaunt factor continuum models.

III. DISCUSSION

The observed spatial and spectral characteristics of H2027+19 suggest several possible interpretations. It is likely to be either (1) an X-ray enhancement similar to that associated with the North Polar Spur (Loop I), which may be an extremely old ($\sim 10^6$ yr) SNR reheated by a subsequent SN explosion (Borken and Iwan 1977); (2) a SNR in the adiabatic expansion phase; or (3) an enhanced emission region surrounding an H I cloud, such as that mentioned in § I.

The first model is unlikely in that the source does not extend appreciably along a loop boundary (Loop II). In fact, H2027+19 appears to be superposed on what may be a large-scale ($\sim 15°$–$20°$) enhancement associated with the inner boundary of Loop II (Berkhuijsen 1971).

The range of allowable values of N_x and T in Figure 2 indicates that we can only weakly constrain model parameters for an adiabatically expanding SNR. We may, however, test the data for consistency under the SNR hypothesis. Using the RS plasma emissivities, we restrict the temperature to $10^{5.8} \lesssim T \lesssim 10^{6.5}$ K. If we then take as a typical value for the ratio of initial SN energy to ambient density $E_0/n \sim 3 \times 10^{51}$ ergs cm^{-3} (Clark and Culhane 1976), the Sedov solution for an adiabatically expanding SNR (see, e.g., Gorenstein and Tucker 1976) yields a remnant diameter $40 \lesssim D \lesssim 60$ pc. With an observed extent $\sim 3°$, this corresponds to a distance $0.75 \lesssim d \lesssim 1.1$ kpc. We may determine if these distance limits are reasonable by using Lα absorption data for stars near the direction of H2027+19 ($l_{II} \sim 62$, $b_{II} \sim -4$). We obtain for 69 Cyg ($l_{II} = 83$, $b_{II} = 10$, $d = 2.1$ kpc), $n_H = 0.17$ cm^{-3} (Savage *et al.* 1977) and for 9 Sge ($l_{II} = 56$, $b_{II} = -4$, $d = 2.8$ kpc), $n_H = 0.13$ cm^{-3} (Bohlin, Savage, and Drake 1978). Assuming an average $n_H \sim 0.15$ cm^{-3}, we estimate a neutral hydrogen column density toward H2027+19 (in the SNR model) of $10^{20.5} < N_H < 10^{20.7}$, which is consistent with the upper limit to the implied total hydrogen column from the X-ray data.

As a further consistency check of the SNR interpretation we may estimate the X-ray luminosity, L_x, of H2027+19 using the range of SNR parameters derived above, and the observed flux, $\sim 2 \times 10^{-11}$ ergs cm^{-2} s^{-1} (0.16–0.4 keV). Correcting for interstellar absorption using the results of Brown and Gould (1970), we obtain $L_x \sim 10^{34}$–10^{35} ergs s^{-1}; our derived values of L_x and D are comparable to those listed by Seward *et al.* (1976) for HB 21 and the Lupus Loop.

We have searched for possible optical and radio counterparts to H2027+19 in the Palomar Sky Survey (E plate), the Hα survey of Dubout-Crillon (1976) and the radio surveys of Berkhuijsen *et al.* (1971) and Haslam *et al.* (1974). Except for a slight increase in radio brightness temperature near the position of our X-ray feature in the Haslam *et al.* (1974) survey, no obvious radio or optical counterpart is apparent. Unfortunately, the extensive SNR survey by Clark and Caswell (1976) is restricted to $|b| < 3°$, and thus does not encompass the region containing H2027+19. The lack of a detectable counterpart, however, is not a conclusive argument against the SNR interpretation, as the radio brightness of an SNR with $D \sim 50$ pc should be $\lesssim 10^{-21}$ W m^{-2} Hz^{-1} sr^{-1}, or roughly at the detection limit of available radio surveys (Clark and Caswell 1976). The absence of Hα filaments is consistent with the expansion of the SNR into a medium of low ambient density: with $L_x \sim 10^{35}$ ergs s^{-1}, $D \sim$ 50 pc, the emissivity function of Raymond, Cox, and Smith (1976), and the assumption that the SNR is a shell source with $\Delta D/D \sim 0.1$, we estimate an ambient density $\sim 10^{-2}$–10^{-1} cm^{-3}. This is somewhat lower than values of n derived for optically observed SNRs such as the Cygnus Loop and Vela, which may account for the lack of an observed optical counterpart if the SNR hypothesis is correct.

While the SNR model is appealing, we suggest another possible interpretation of our data in which an H I cloud is imbedded in the interior of a hot SNR cavity. Under these conditions, cloud material is evaporated into the ambient medium, creating a region of enhanced soft X-ray emission (McKee and Cowie 1977; McKee and Ostriker 1977). Hayakawa *et al.* (1979) have proposed this interpretation for the Lupus Loop. One important requirement is that the cloud be located inside a known SNR cavity; in the case of the Lupus Loop, radio continuum Loop I is identified by Hayakawa *et al.* (1979) as the surrounding SNR. In the case of H 2027+19, Loop II is an obvious choice, as some portions of it have been detected as soft X-ray enhancements (Hayakawa *et al.* 1977; Iwanami *et al.* 1979), and H2027+19 lies within the radio loop boundary.

If the source is an enhanced emission region, then with the distance to the center of Loop II estimated at 110 ± 40 pc (Spoelstra 1972), the diameter of H2027+19 would be ~ 5 $(d/100)$ pc, and it would have a luminosity $L_x \sim 2 \times 10^{31}$ $(d/100)^2$ ergs s^{-1}. Such a luminosity would require an emission integral $\int n_e^2 dv \sim 10^{54}$ cm^{-3} (using $\Lambda = 2 \times 10^{-23}$ ergs cm^{-3} s^{-1} from Raymond, Cox, and Smith (1976), for $T = 10^{6.3}$ K).

Using the differential emission measure calculated by McKee and Cowie (1977) for a classically evaporating cloud, and assuming the cloud is embedded in a medium characterized by $T \sim 10^{6.3}$ K and $p \sim 10^4$ cm^{-3} K, we estimate an emission integral of $\sim 10^{53}$ cm^{-3}. Allowing for the parameter uncertainties noted above, we find this calculated value in reasonable agreement with the observed emission integral. The size of H2027+19 is slightly larger than the diameter of a typical cloud in the model ($\sim$2–3 pc), as would be expected. However, the temperature we must assume is significantly higher than that suggested by McKee and Ostriker for the nearby hot ISM. For the evaporating cloud model to apply, we require that the interior of Loop II be at $T > 10^{6.3}$ K (RS). This is supported by the spectral hardening seen by Hayakawa *et al.* (1978) interior to Loop II; these authors derive a temperature of $10^{6.25 \pm 0.1}$ K for the loop interior. Caution must be exercised, however, in comparing our results to those of Hayakawa *et al.* (1978), as a different plasma emissivity function (Kato 1976) was used. We note that if the interior of Loop II were closer to the median temperature of hot, ionized regions suggested by McKee and Ostriker ($T \sim 10^{5.7}$ K), then the enhanced emission would most likely appear as a feature in the EUV background, as suggested by Stern and Bowyer (1979).

IV. CONCLUSION

We find that the physical interpretation of H2027+19 as either an old SNR ($D \sim 50$ pc, $L_x \sim 10^{34}$–10^{35} ergs s^{-1}, $T \sim 10^{6.0}$ K), or an enhanced emission region surrounding an H I cloud in an SNR cavity ($L_x \sim 4 \times 10^{31}$ ergs s^{-1}, $D \sim 5$ pc), is consistent with our data. The multiple discrete source hypothesis, though unlikely, may be conclusively tested by observations on X-ray imaging satellites such as *Einstein* (*HEAO 2*). To discriminate between the SNR and H I cloud models, more sensitive radio continuum and Hα surveys of the region are needed, as well as better spectral data in the soft X-ray and possibly EUV bands.

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REFERENCES

Agrawal, P. C., and Riegler, G. R. 1979*a*, *Bull. AAS*, **10**, 617.
———. 1979*b*, *Bull. AAS*, **11**, 462.
Berkhuijsen, E. M. 1971, *Astr. Ap.*, **14**, 359.
Bohlin, R. C., Savage, B. D., and Drake, J. F. 1978, *Ap. J.*, **224**, 132.
Borken, R., and Iwan, D. 1977, *Ap. J.*, **218**, 511.
Brown, R. L., and Gould, R. J. 1970, *Phys. Rev. D*, **1**, 2252.
Cash, W. 1976, *Astr. Ap.*, **52**, 307.
Clark, D. H., and Caswell, J. L. 1976, *M.N.R.A.S.*, **174**, 267.
Clark, D. H., and Culhane, J. L. 1976, *M.N.R.A.S.*, **175**, 543.
Culhane, J. L. 1977, in *Supernovae*, ed. D. N. Schramm (Dordrecht: Reidel), pp. 29–51.
Dubout-Crillon, R. 1976, *Astr. Ap. Suppl.*, **25**, 25.
Gorenstein, P., and Tucker, W. H. 1976, *Ann. Rev. Astr. Ap.*, **14**, 373.
Haslam, C. G. T., Wilson, W. E., Graham, D. A., and Hunt, G. C. 1974, *Astr. Ap. Suppl.*, **13**, 359.
Hayakawa, S., Kato, T., Nagase, F., Yamashita, K., Murakami, T., and Tanaka, Y. 1977, *Ap. J.* (*Letters*), **213**, L109.
Hayakawa, S., Kato, T., Nagase, F., Yamashita, K., and Tanaka, Y. 1978, *Astr. Ap.*, **62**, 21.
———. 1979, *Pub. Astr. Soc. Japan*, **31**, 71.
Iwanami, H., Kunieda, H., Nagase, F., Yamashita, K., and Murakami, T. 1979, *Ap. Space Sci.*, **61**, 217.
Kato, T. 1976 *Ap. J. Suppl.*, **30**, 397.
Lampton, M., Margon, B., and Bowyer, S. 1976, *Ap. J.*, **208**, 177.

McKee, C. F., and Cowie, L. L. 1977, *Ap. J.*, **215**, 213.
McKee, C. F., and Ostriker, J. P. 1977, *Ap. J.*, **218**, 148.
Palmieri, T. M., Burginyon, G. A., Hill, R. A., Scudder, J. K., and Seward, F. D. 1972, *Ap. J.*, **177**, 387.
Raymond, J. C., Cox, D. P., and Smith, B. W. 1976, *Ap. J.*, **204**, 290.
Raymond, J. C., and Smith, B. W. 1977, *Ap. J. Suppl.*, **35**, 419.
———. 1980, in preparation (RS).
Riegler, G. R., Agrawal, P. C., and Gull, S. F. 1980, *Ap. J. (Letters)*, **235**, L71.
Rothschild, *et al.* 1979, *Space Sci. Inst.*, **4**, 269.
Savage, B. D., Bohlin, R. C., Drake, J. F., and Budich, W. 1977, *Ap. J.*, **216**, 291.
Seward, F. D., *et al.* 1976, *Ap. J.*, **205**, 238.
Spoelstra, T. A. Th. 1972, *Astr. Ap.*, **21**, 61.
Stern, R., and Bowyer, S. 1979, *Ap. J.*, **230**, 755.
Tuohy, I., *et al.* 1979, *Ap. J. (Letters)*, **230**, L27.
Winkler, P. F., Hearn, D. R., Richardson, J. A., and Behnken, J. M. 1979, *Ap. J. (Letters)*, **229**, L123.

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