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THE SOFT X-RAY SPECTRUM OF THE PERSEUS CLUSTER

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ABSTRACT

The X-ray spectrum of the Perseus cluster in the range 0.1–4.0 keV has been observed. Contrary to the results of previous low-energy rocket observations, no large flux of soft X-rays was found. The X-ray spectrum from 0.1 to 56 keV is consistent with bremsstrahlung from an intracluster gas with $T \approx 10^8$ K, attenuated by the interstellar column density inferred from 21-cm observations. The low-energy X-ray spectrum is not consistent with a nonthermal power-law model with the same slope as that observed at higher energies. The mass of hot intracluster gas required to produce the observed X-ray flux is a small fraction of the gravitational binding mass. The soft X-ray flux, when combined with limits on the radio flux, implies that the cluster is not gravitationally bound by ionized gas at any temperature.

Subject headings: galaxies, clusters of — intergalactic medium — spectra, X-ray — X-ray sources

I. INTRODUCTION

The X-ray spectrum of the Perseus cluster has been measured by a number of groups, and the results are widely divergent. The character of this spectrum is especially important since results obtained by the *Uhuru* satellite show that many rich clusters of galaxies are extended sources of X-ray emission (Kellogg *et al.* 1973). Two competing models for the origin of this radiation have been widely discussed. The X-ray emission might result from inverse Compton scattering involving microwave background photons and relativistic electrons which are inferred to be present from the observation of extended, nonthermal radio sources in these clusters (Bridle and Feldman 1972; Perola and Reinhardt 1972; Brecher and Burbidge 1972). Alternatively, the X-ray emission may be thermal bremsstrahlung produced by hot ($\sim 10^8$ K) intracluster gas (Felten *et al.* 1966; Lea *et al.* 1973). One may hope that observations of the X-ray spectra of these clusters may distinguish between these models.

The situation in the case of the Perseus cluster is particularly unclear. The *Uhuru* spectral results were found to be inconsistent with an exponential spectrum by Forman *et al.* (1972), who obtained a power-law fit with $dN(E)/dE \propto E^{-2.09}$. More recently the spectrum has been found consistent with thermal bremsstrahlung, including an energy-dependent Gaunt factor (Margon 1973), from gas at $kT = 8.5(\pm 1)$ keV (Forman, quoted in Lea *et al.* 1973). Most previous experiments which included data at softer energies have found large fluxes of soft X-rays and rather steep spectra for Per X-1 (Fritz *et al.* 1971; Hayakawa *et al.* 1972; Agrawal, Long, and Garmire 1974). Soft X-ray observations of the core of the Perseus cluster have recently been made with the *Copernicus* telescope (Fabian *et al.* 1974). These authors report that their observations with high spatial resolution ($\lesssim 10'$) do not show the large low-energy fluxes obtained in the rocket observations, but they suggest that this apparent discrepancy would be resolved if the low-energy flux emanated from an extended region of low surface brightness.

Observations at high energies have also failed to establish whether the X-ray spectrum of the Perseus cluster is thermal or nonthermal. Results obtained in the 7–56 keV range on OSO-7 by Ulmer, Baity, and Peterson (1973) suggest that the spectrum at higher energies is steeper than the power law obtained by Forman *et al.* (1972) (as expected for a thermal model), but the authors do not regard their data as inconsistent with an extrapolation of the *Uhuru* power-law spectrum. In contrast to this result is a balloon observation in the range 53–93 keV by Bui-Van, Hurley, and Vedrenne (1974) which yielded a positive flux exceeding the OSO-7 upper limits at somewhat lower energies.

In this paper we present results of a rocket observation of the Perseus cluster in the energy range 0.1–4.0 keV. These data, obtained with a field of view optimized for observations of the whole cluster, reveal no evidence for a large low-energy flux associated with the Perseus cluster. Instead we find that the soft X-ray spectrum is consistent with an extrapolation of a thermal bremsstrahlung spectrum which fits higher-energy data. Our data can also be fitted with power-law models, but the spectral index we derive is substantially smaller than the index reported at higher energies (Forman *et al.* 1972; Ulmer *et al.* 1973). If the extended X-ray emission originates in hot intracluster gas, the mass of gas required is only a fraction of the gravitational binding mass. In addition, upper limits on the low-energy X-ray and radio fluxes from the Perseus cluster limit the amount of cooler gas which may be present. The constraints are similar to those which apply to the Coma cluster (Davidsen, Bowyer, and Welch 1973) and imply that the Perseus cluster is also not bound by ionized gas at any temperature.

II. X-RAY OBSERVATIONS

The data discussed here were obtained by a thin-window (85 μg cm^{-2} polypropylene, with 35 μg cm^{-2}

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carbon coating), large-area (633 cm^2) proportional counter with approximately 2° × 2°.5 collimation (FWHM) which was launched from White Sands Missile Range aboard a Black Brant VC rocket at UT 0408 on 1973 February 9. Detailed parameters of this detector have been presented elsewhere (Bowyer *et al.* 1974). A slow roll brought the Perseus cluster into the field of view 290 seconds into the flight, when the rocket altitude was 200 km. The payload pointing at this point was determined from an analysis of stellar transits observed by a far ultraviolet telescope/photometer similar to one described by Holberg, Bowyer, and Lampton (1973), along with telemetered data on the attitude control system performance. The resulting scan pattern is accurate to ~0°.25. The data were processed in flight by a 64-channel pulse-height analyzer to measure the photon energy distribution in the range 0.07–5.0 keV. An in-flight calibration of the gain of the detector was obtained by observing the Crab nebula immediately after the Perseus cluster. The gain was determined by requiring that the spectrum derived for the Crab agree with the well-determined published parameters for that source and is accurate to better than 10 percent.

A total of 346 ± 18 photons were detected from the Perseus cluster. The pulse-height spectrum was analyzed in the manner described in detail by Cruddace *et al.* (1972). Thermal bremsstrahlung and power-law spectra, together with photoelectric absorption in the interstellar medium (Cruddace *et al.* 1974), were folded with the detector response function and the results compared with the observed pulse-height spectra using the χ^2 test. The parameters were varied and the range of values yielding acceptable fits was determined. In Figure 1 we have displayed the contours, for both thermal and nonthermal models, within which the true values of the parameters are contained with 90 percent confidence. These contours give the parameter values for which $\chi^2 = \chi_{\min}^2 + \chi_3^2(0.9)$, where $\chi_3^2(0.9) = 6.25$ is the 90 percent confidence value of a χ^2 variate with 3 degrees of freedom (Margon *et al.* 1975). In spite of the rather good statistics, the contours obtained from our data alone do not close within the parameter range of interest

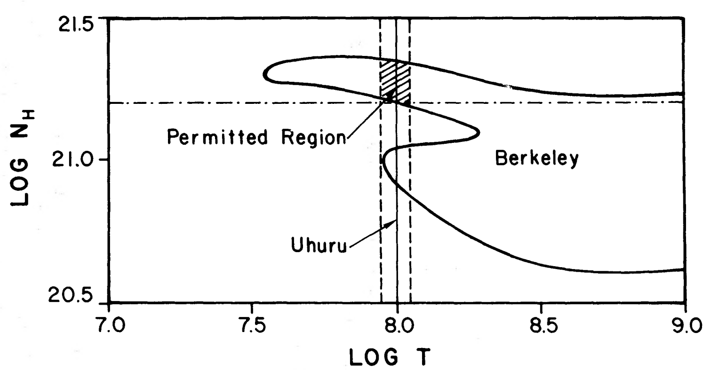

FIG. 1*a*

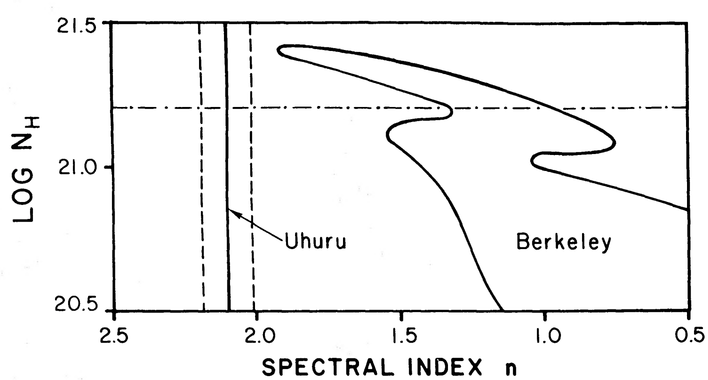

FIG. 1*b*

FIG. 1*a*.—Limits on the temperature T and hydrogen column density N_H deduced from thermal bremsstrahlung fits to the X-ray spectrum of the Perseus cluster. With 58 degrees of freedom, the best fitting χ^2 was 59; the contour was drawn at $\chi^2 = 65$. The dot-dash line is the lower limit on N_H inferred from 21-cm observations. The permitted region contains the parameter values allowed by the present data combined with results from *Uhuru*.

FIG. 1*b*.—Limits on the spectral index n and hydrogen column density N_H for power-law fits to the Perseus X-ray spectrum. With 58 degrees of freedom, the best fitting χ^2 was 57; the contour was drawn at $\chi^2 = 63$. The absence of a permitted region implies that the X-ray spectrum is not adequately described by a single power law.

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because of the small energy range over which our experiment is sensitive. Nevertheless, these data, when combined with other data, do lead to interesting conclusions.

In Figure 1*a* we show the limits on temperature T and column density N_H obtained from fitting thermal bremsstrahlung spectra to our data. Also shown is the temperature derived from *Uhuru* data (Lea *et al.* 1973) and the column density $N_H = 1.6 \times 10^{21}$ cm^{-2} deduced from 21-cm observations (Hughes, Thompson, and Colvin 1971) in the direction of the Perseus cluster. This value of N_H may be regarded as providing a lower limit on the X-ray attenuation since there are other sources of attenuation which could in principle contribute. These include self-absorption in the source, absorption in the intergalactic medium, and interstellar absorption in our Galaxy associated with molecular hydrogen.

From the results displayed in Figure 1*a* we conclude that thermal bremsstrahlung from gas at $T = 10^8$ K, attenuated by the column density of interstellar material observed in our Galaxy, yields a good fit to both the *Uhuru* and Berkeley data. We fit a thermal bremsstrahlung spectrum having the form

$$F(E) = Ag(E, T)T_8{}^{-1/2}e^{-E/kT} \exp[-\sigma(E)N_H] \quad \text{keV(cm}^2\text{ s keV)}^{-1} \qquad (1)$$

to our data, setting $T_8 = 1$ and $N_H = 1.6 \times 10^{21}$ cm^{-2}. This spectrum yields a confidence of 29 percent with $A = 0.12$.

The constraints on power-law spectra which are obtained from our data and the *Uhuru* results are shown in Figure 1*b*. A single power law does not appear to be consistent with the results of both experiments. The low-energy data are well fitted only by power-law spectra which are flatter than the $E^{-2.09}$ obtained by Forman *et al.* (1972). However, if the error on the spectral index derived from *Uhuru* data has been underestimated as suggested by Margon *et al.* (1975), a single power law may provide an adequate fit. An argument against this possibility is the conclusion of Ulmer *et al.* (1973) that the Perseus spectrum is unlikely to be flatter than E^{-2} in the 7–56 keV range. Thus a power-law model for the Perseus X-ray spectrum probably requires a spectral break in order to fit all the existing data.

Our data are consistent with values of N_H up to 2.5×10^{21} cm^{-2}. Thus the total amount of gas in this direction does not exceed the value deduced from 21-cm observations by more than about 50 percent. This limit agrees with the expected fraction of interstellar gas which might be concealed in the form of molecular hydrogen (Spitzer *et al.* 1973) in this direction, for which $E(B - V) = 0.10$ (Sandage 1972).

In Figure 2 we show our spectral results for the Perseus cluster, along with all previously published detections. The smooth curve is the thermal bremsstrahlung spectrum (eq. [1]) which fits our data and the data from *Uhuru*. This spectrum also provides a good fit to the OSO-7 data (Ulmer *et al.* 1973). Both the spectral shape and the total flux which we observe at low energies is in conflict with previous soft X-ray rocket experiments (Fritz *et al.* 1971; Hayakawa *et al.* 1972; Agrawal *et al.* 1974). The discrepancy between our data and these previous results might be the result of the differing fields of view of the various experiments. The large fields of view employed in previous rocket measurements led all of the authors to caution that their results might not apply to the Perseus cluster. Indeed, the existence of another X-ray source within a few degrees of the Perseus cluster has been reported by Heinz *et al.* (1973), although it is by no means certain that this source provides the large low-energy fluxes which have been reported. Our results are compatible with the high spatial resolution *Copernicus* soft X-ray measurements (Fabian *et al.* 1974) which also showed no evidence for a large low-energy flux. If the hypothesis of Fabian *et al.* that the large flux of soft X-rays originates in an extended source of low surface brightness were correct, our results imply that $\leqslant 10$ percent of the flux near 0.5 keV could originate within 1° of the cluster center, and such a source would therefore have to be much larger than the observed extent of the galaxy distribution.

III. INTRACLUSTER GAS

A variety of evidence now supports the hypothesis that the X-ray emission from clusters of galaxies is thermal in origin. The spectral data presented here for the Perseus cluster are consistent with this hypothesis, although the alternative nonthermal model has not been entirely excluded. Gorenstein, Harris, and Gursky (1972) and Gorenstein *et al.* (1973) have presented spectral data for the Coma and Virgo clusters which support a thermal origin for the X-rays in those clusters. Lea *et al.* (1973) found that the *Uhuru* data on the spatial distribution of X-rays from Coma, Virgo, and Perseus were well fitted by thermal emission from an isothermal distribution of gas and were not well fitted by nonthermal models in which the emission is proportional to the first power of the density (inverse Compton scattering, for example). Margon (1973) and Silk (1973) have commented that the thermal velocity of the X-ray plasma in the Coma cluster is comparable to the random velocity of the galaxies, and this is true of the Perseus cluster as well. This rough equality is expected in a variety of models which involve intracluster gas. Finally, Solinger and Tucker (1972) have discussed the correlation of cluster X-ray luminosities and velocity dispersions, a result which is readily understood in terms of thermal models.

The observed X-ray spectrum may be used to calculate the mass of hot gas which may be present in the Perseus cluster. The distribution of X-ray surface brightness observed by *Uhuru* has been found consistent with an isothermal sphere with a core radius of $15' \pm 2'$ (Lea *et al.* 1973). *Copernicus* observations of the cluster core (Fabian *et al.* 1974) are consistent with a radius of 14′. Wolff *et al.* (1974) have found that the

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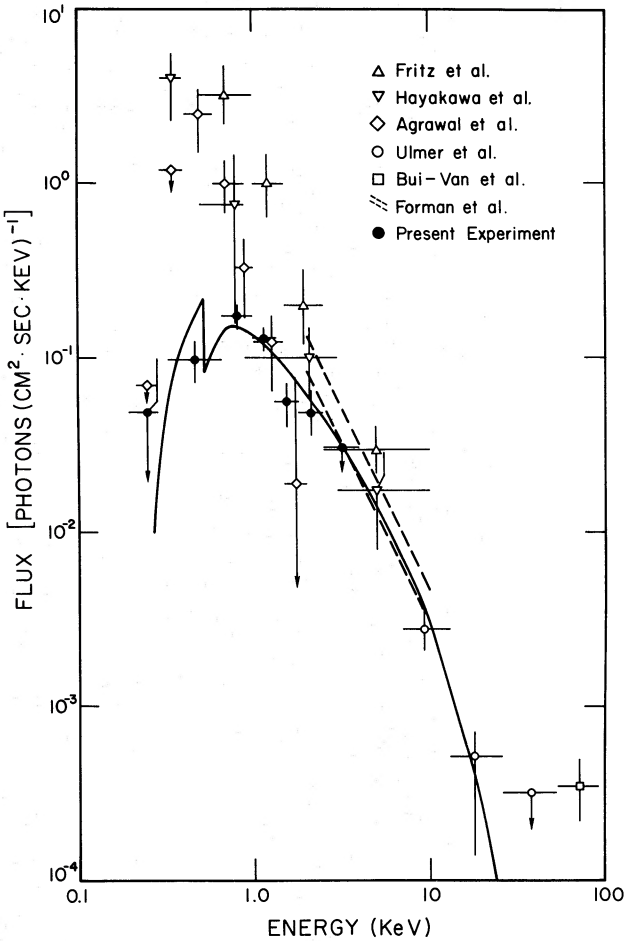

FIG. 2.—X-ray spectrum of the Perseus cluster. All published detections of the source are included. The smooth curve, which fits the present data as well as the *Uhuru* and OSO-7 observations, corresponds to thermal bremsstrahlung from gas at $T = 1.0 \times 10^8$ K with interstellar absorption corresponding to $N_H = 1.6 \times 10^{21}$ cm^{-2}. The prominent feature at 0.53 keV is the interstellar oxygen *K*-edge. Discontinuities due to other elements are much smaller. Error bars are $\pm 1\ \sigma$ statistical errors. The large low-energy fluxes previously reported are not confirmed in this observation.

X-ray brightness distribution is asymmetric and is not satisfactorily modeled by an isothermal sphere. Fits were improved by a point source at the position of NGC 1275; the required intensities are less than 16 percent of the total flux.

The X-ray bremsstrahlung emission from an isothermal sphere of H with 10 percent He and a core radius of a_{gas} in units of 1 Mpc is

$$F(E) = 2.4 g(E, T) T_8^{-1/2} e^{-E/kt} e^{-\tau(E)} \times \sigma_{1000}{}^4 a_{\text{gas}}{}^3 a_{\text{gal}}{}^{-4} D_{100}{}^{-2} C \omega^2 \text{ keV(cm}^2\text{ s keV)}^{-1} . \quad (2)$$

Here $g(E, T)$ is the Gaunt factor, T_8 is the temperature in units of 10^8 K, σ_{1000} is the line of sight velocity dispersion of galaxies in the core in units of 1000 km s^{-1}, a_{gal} is the core radius in units of 1 Mpc, D_{100} is the distance to the cluster in units of 100 Mpc, $C = \langle n_e^2 \rangle / \langle n_e \rangle^2$ is the clumpiness factor, $\omega \equiv \rho(0)/\rho_c(0)$ is the central gas density divided by the critical density $\rho_c(0) = 9\sigma^2/4\pi G a_{\text{gal}}{}^2$ (Rood *et al.* 1972) necessary to gravitationally bind the cluster, and $\tau(E)$ is the optical depth of the medium intervening between source and observer. For Perseus we have $\sigma = 1457$ km s^{-1}, $a_{\text{gal}} = 0.16$ Mpc (Bahcall 1974), $D = 73$ Mpc (assuming $H_0 = 75$ km s^{-1} Mpc^{-1}). From equation (2) and our observed spectrum in equation (1), we obtain $\omega \leq 0.03 C^{-1/2}$ for $a_{\text{gas}} = 0.16$ Mpc, and $\omega \leq 0.012 C^{-1/2}$ for $a_{\text{gas}} = 0.3$ Mpc. Thus, if the gas is smoothly distributed similar to the galaxy distribution, the amount required to produce the observed X-rays is ~ 3 percent of the mass required to bind the cluster. If the gas is clumpy, or has a broader distribution than the galaxies, the observed X-rays will be produced by a smaller density of material.

We have also considered the possibility that the Perseus cluster contains a substantial amount of cooler ionized gas with $a_{\text{gas}} = a_{\text{gal}}$. Limits on the temperature and clumpiness of such gas obtained from Lα and previous X-ray observations have been discussed by Bohlin, Henry, and Swandic (1973).

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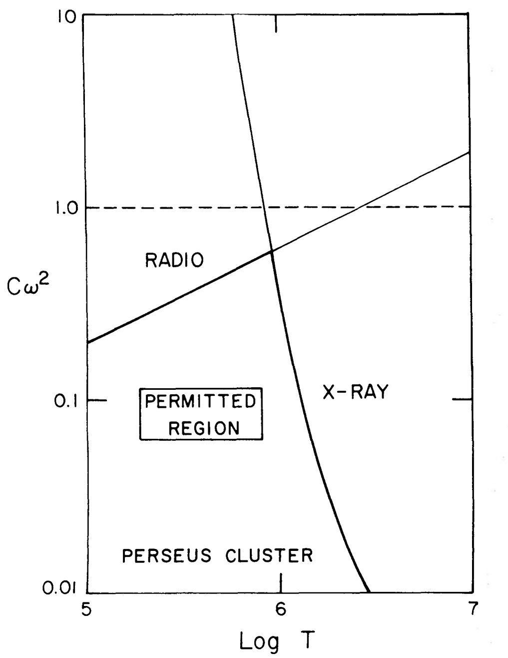

FIG. 3.—Observational limits on clumpiness C, fraction ω of a binding mass, and temperature T for ionized intergalactic gas in the Perseus cluster. Binding the cluster required $C\omega^2 \geq 1$. The X-ray limit is obtained from the present observations. The radio limit is from Ryle and Windram (1968).

Stronger limits may be obtained from our soft X-ray observations and from limits on the radio brightness of the cluster. The observed X-ray flux from Perseus at 0.5 keV is $F(0.5) = 0.10 \pm 0.05$ keV (cm^2 s keV)$^{-1}$. Thus, a conservative (3 σ) upper limit on the flux from cool ionized gas is $F(0.5) \leq 0.25$ keV (cm^2 s keV)$^{-1}$. Inserting this in equation (2), we obtain an upper limit on $C\omega^2$ as a function of the temperature T of the gas. This limit is shown in Figure 3.

Equation (2) may be rewritten in a form which is more convenient for application to radio observations:

$$F_\nu = 0.16 T_6^{-1/2} \sigma_{1000}^{4} a_{\rm gas}^{3} a_{\rm gal}^{-4} D_{100}^{-2} C\omega^2 \text{ jansky}, \tag{3}$$

where T_6 is the intracluster plasma temperature in units of 10^6 K and we have set $g(E, T) = 10$, appropriate for radio frequencies. The complicated radio structure of the Perseus cluster has been discussed by Ryle and Windram (1968). In addition to several compact sources, the cluster contains an extended component, designated 3C 84 B, whose size is comparable to that of the cluster core. This component does not arise through bremsstrahlung in the intracluster medium since it has a nonthermal spectrum, but its flux provides an upper limit on the emission of any ionized gas which may be present. The total flux from 3C 84 B at 3000 MHz is 2 ± 1 Jy (Ryle and Windram 1968). We will take 5 Jy as a conservative upper limit. Inserted in equation (3), this yields the radio limit on $C\omega^2$ which is shown in Figure 3. The combined results of the soft X-ray and radio observations imply that $C\omega^2 < 1$ for all T. Thus, like the Coma cluster (Davidsen, Bowyer, and Welch 1973), the Perseus cluster is not bound by ionized gas.

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REFERENCES

Agrawal, P. C., Long, K., and Garmire, G. P. 1974, *Ap. and Space Sci.*, **28**, 185.
Bahcall, N. 1974, *Ap. J.*, **187**, 439.
Bohlin, R. C., Henry, R. C., and Swandic, J. R. 1973, *Ap. J.*, **182**, 1.
Bowyer, S., Margon, B., Lampton, M., and Cruddace, R. 1974, *Ap. J.*, **190**, 285.
Brecher, K., and Burbidge, G. 1972, *Nature*, **237**, 440.
Bridle, A., and Feldman, P. A. 1972, *Nature Phys. Sci.*, **235**, 168.
Bui-Van, A., Hurley, K., and Vedrenne, G. 1974, *Ap. J.*, **188**, 217.
Cruddace, R., Bowyer, S., Lampton, M., Mack, J., and Margon, B. 1972, *Ap. J.*, **174**, 529.
Cruddace, R., Paresce, F., Bowyer, S., and Lampton, M. 1974, *Ap. J.*, **187**, 497.
Davidsen, A., Bowyer, S., and Welch, J. 1973, *Ap. J. (Letters)*, **186**, L119.
Fabian, A., Zarnecki, J., Culhane, J., Hawkins, F., Peacock, A., Pounds, K., and Parkinson, J. H. 1974, *Ap. J. (Letters)*, **189**, L59.
Felten, J., Gould, R., Stein, W., and Woolf, N. 1966, *Ap. J.*, **146**, 955.
Forman, W., Kellogg, E., Gursky, H., Tananbaum, H., and Giacconi, R. 1972, *Ap. J.*, **178**, 309.
Fritz, G., Davidsen, A., Meekins, J., and Friedman, H. 1971, *Ap. J. (Letters)*, **164**, L81.
Gorenstein, P., Harris, B., and Gursky, H. 1972, *Ap. J. (Letters)*, **172**, L41.
Gorenstein, P., Bjorkholm, P., Harris, B., and Harnden, F. R. Jr. 1973, *Ap. J. (Letters)*, **183**, L57.
Hayakawa, S., Kato, T., Nishimura, K., Tanaka, Y., and Yamashita, K. 1972, *Ap. and Space Sci.*, **17**, 30.
Heinz, C., Bradt, H., Clark, G., Lewin, W., and Sprott, G. 1973, *IAU Circ.*, No. 2540.
Holberg, J., Bowyer, S., and Lampton, M. 1973, *Ap. J. (Letters)*, **180**, L55.
Hughes, M. P., Thompson, A. R., and Colvin, R. S. 1971, *Ap. J. Suppl.*, No. 200, **23**, 223.
Kellogg, E., Murray, S., Giacconi, R., Tananbaum, H., and Gursky, H. 1973, *Ap. J. (Letters)*, **185**, L13.
Lea, S., Silk, J., Kellogg, E., and Murray, S. 1973, *Ap. J. (Letters)*, **184**, L105.
Margon, B. 1973, *Ap. J.*, **184**, 323.
Margon, B., Lampton, M., Bowyer, S., and Cruddace, R. 1975, *Ap. J.*, **197**, 25.
Perola, G. C. and Reinhardt, M. 1972, *Astr. and Ap.*, **17**, 432.
Rood, H. J., Page, T., Kintner, E. C., and King, I. R. 1972, *Ap. J.*, **175**, 627.
Ryle, M., and Windram, M. D. 1968, *M.N.R.A.S.*, **138**, 1.
Sandage, A. 1972, *Ap. J.*, **178**, 1.
Silk, J. 1973, *ARAA*, **11**, 269.
Solinger, A. B., and Tucker, W. H. 1972, *Ap. J. (Letters)*, **175**, L107.

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1975ApJ...198....1D

Spitzer, L., Drake, J. E., Jenkins, E. B., Morton, D. C., Rogerson, J. B., and York, D. G. 1973, *Ap. J.* (*Letters*), **181**, L116.
Ulmer, M. P., Baity, W. A., and Peterson, L. E. 1973, *Ap. J.*, **183**, 15.
Wolff, R. S., Helava, H., Kifune, T., and Weisskopf, M. C. 1974, *Ap. J.* (*Letters*), **193**, L53.

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