THE ASTROPHYSICAL JOURNAL, 217:L143–L147, 1977 November 1

AN OPTICAL SEARCH FOR IONIZED HYDROGEN IN GLOBULAR CLUSTERS. II.

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Received 1977 June 15; accepted 1977 July 29

ABSTRACT

Photoelectric Hα line profiles obtained with a single-étalon Fabry-Perot interferometer are used to set probable upper limits on the presence of ionized hydrogen in 30 galactic and one extragalactic globular clusters, thus bringing the number of clusters examined in a uniform manner to 48. No ionized gas is detected in any of the clusters. Among the most stringent limits ($M_{\rm H\,II} < 1\,M_\odot$) on accumulated gas are those for four clusters (NGC 1851, 6441, 6624, and 7078) commonly associated with X-ray sources. For NGC 104 (47 Tuc), line profile comparisons suggest that roughly comparable volumes of core and halo differ by $<0.03\,M_\odot$ in the amount of (undetected) ionized hydrogen.

Radial velocities, also crucial to 21 cm emission studies where cluster emission must be disentangled from galactic H I emission, are discussed for several clusters. For NGC 6441 the commonly used velocity, -70 km s^{-1}, is in error; a preliminary revised value is $+13$ km s^{-1}.

Subject headings: clusters: globular — galaxies: Magellanic Clouds — interstellar: matter — radial velocities — stars: mass loss — X-rays: sources

I. INTRODUCTION

Mass loss resulting from normal, post–main-sequence stellar evolution is thought to form an interstellar medium in globular clusters, yet observational constraints on the presence of such a medium are becoming increasingly stringent. In Paper I of this series (Smith, Hesser, and Shawl 1976), we applied a single-étalon Fabry-Perot interferometer to the problem of detecting Hα emission in the cores of 26 globular clusters. With the adoption of certain assumptions, our photoelectric Hα line profiles may be interpreted to yield probable upper limits on the presence of ionized hydrogen; for brevity we refer the reader to Paper I for a discussion of the assumptions, except to note that the single most important one is that any gas present will be distributed uniformly over the volume defined by the cluster core radius (King 1962, 1966). In this *Letter* we report new and/or improved results for 31 globular clusters, including the X-ray globular clusters NGC 1851, 6441, 6624, and 7078.

Previous work on interstellar matter in globular clusters was reviewed in Paper I, where the null results from radio work on neutral and ionized hydrogen were referenced and compared with our optical values and with the theoretical models;[1] and it was shown that a typical cluster apparently has less than a few solar masses of combined H I and H II. Since Paper I was written, Faulkner and Freeman (1977) have presented optical results for ionized hydrogen in five globular clusters and discussed time-independent flow models in considerable detail. Time dependence has recently been included in their models by VandenBerg and Faulkner (1977), who find that in the absence of some external heating mechanism(s), $>50\,M_\odot$ of gas (mostly neutral) will accumulate in the core of a $10^6\,M_\odot$ globular cluster over 10^7 years. A recent attempt (Troland, Hesser, and Heiles 1978) to detect 115 GHz $^{12}C^{16}O$ emission from suspected dark clouds (Roberts 1960) in six globular clusters and from the cores of three X-ray globular clusters was unsuccessful; however, the system sensitivity was insufficient to rule out the possibility that the clouds might be typical galactic dust clouds. Kerr, Bowers, and Knapp (1976) have reported stringent new limits on H I for several southern globular clusters, as well as failure to detect the 1612 MHz OH line; and Grindlay and Liller (1976) have suggested from Hα measurements that ionized gas in globulars amounts to $<0.1\,M_\odot$.

II. RADIAL VELOCITIES

The detection of ionized hydrogen with the Fabry-Perot interferometer depends upon knowing the cluster velocity from independent spectroscopic means with a

* Operated by the Association of Universities for Research in Astronomy, Inc., under contract No. NSF-C866 with the National Science Foundation.

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[1] We inadvertently failed to refer in Paper I to an important theoretical paper by Burke (1968), who anticipated much of the later work on this problem by several years.

precision of $\sim$50 km s^{-1} in order to identify the order of interference. However, once the order is known, the Fabry-Perot data can also be used to derive precise radial velocities. On average the agreement between our velocities and the classical, low-dispersion, spectrographic values of Mayall (1946) and Kinman (1959), $V_{\rm MK}$, is very good, i.e., much better than 50 km s^{-1} in most individual cases. However, a particularly important discrepancy that arose in Paper I, namely that of NGC 6441, has now been resolved and merits detailed discussion.

NGC 6441 is the compact, metal-rich cluster (Hesser and Hartwick 1976) apparently associated with 3U 1746−47 (Giacconi *et al.* 1974). As noted in Paper I, the $V_{\rm MK}$ value coincides with the maximum of the interferometer output, implying that strong Hα emission is present. However, on the basis of a single image-tube spectrogram (obtained on a defective emulsion) which yielded $V \approx +54$ km s^{-1}, we cautioned that $V_{\rm MK}$ might be in error. Last season we obtained much higher quality spectrograms with the Boller and Chivens RCA 33063 image-tube spectrograph on the 1 m Yale-Tololo telescope. These 122 Å mm^{-1} spectra were widened 0.5 mm on baked IIIa-J plates by trailing the in-focus image of the cluster along the slit. Numerous IAU radial-velocity standard stars were observed before and after each cluster observation. We have measured several plates, including two exposures each of NGC 6388 and 6441, with the Arcturus measuring engine of the Dominion Astrophysical Observatory.

For NGC 6441 differential measurement with respect to the similarly metal-rich cluster NGC 6388 should yield a reliable velocity estimate in which wavelength uncertainties largely cancel. We take $V_{6388} = +81$ km s^{-1} (Kinman 1959), from which our spectra of both clusters imply that $V_{6441} \approx +22$ km s^{-1} instead of $V_{\rm MK} = -70$ km s^{-1} (Mayall 1946). Dr. Garth Illingworth, on the basis of a quick comparative study of his Mount Stromlo coudé spectra (Illingworth 1973) of NGC 104, 6388, and 6441, confirms that the velocity of NGC 6441 must lie between that of NGC 104 and that of NGC 6388; he estimates $V_{6441} = +10 \pm 20$ km s^{-1}. The minima of the Fabry-Perot profiles observed on two nights in 1975 (Paper I, Fig. 1*d*[2]) and one in 1976 (this paper) correspond to $V = +12 \pm 4$ km s^{-1} (s.e. of the mean). Consequently we conclude that the value obtained by Mayall (1946), in spite of internal consistency among individual measures, is systematically in error; it follows immediately that NGC 6441 does *not* show strong Hα emission.

Several other cases of radial velocity uncertainties are mentioned in the footnotes to Table 1; until we can ob-

[2] The ordinate labels to Figs. 1*d* and 1*e* of Paper I should read "counts/2 seconds," not "counts/100 seconds."

TABLE 1

Results From Interferometrically-Measured Hα Line Profiles For Globular Clusters

Cluster NGC	Cluster Other	Date (D/M/Y)	D_a (%)	R	D (%)	C_1 (s^{-1})	C_2 (s^{-1})	d (kpc)	D_c (pc)	θ_c (arc minutes)	θ' (arc minutes)	M_1 (solar masses)	M_2 (solar masses)
104*	47 Tuc	21/08/75	9.4	5.6	52.8	120	447	4.0	1.0	0.95	1.2	1.2	2.3
	(Core)	22/08/75	12.8	5.6	71.6	26.3	410				1.2	0.5	2.1
		03/09/75	11.9	5.6	66.5	39.1	340				2.0	1.1	3.2
		03/08/76	10.5	5.6	58.9	85.3	448				1.2	1.0	2.2
	North	21/08/75	9.8	5.6	54.9	32.0	138.6				1.2	0.6	1.2
		22/08/75	12.5	5.6	69.8	4.8	58.7				1.2	0.2	0.8
121	(SMC)	02/09/75	19.6::	5.6	100::	0.0::	2.3	63	24.4	1.3	2.0	-	500::
288		15/08/75	12.2	5.6	68.8	0.3	2.8	9.4	8.7	3.2	2.0	9.1	28.1
362		16/08/75	10.4	4.1	42.6	17.0	48.1	9.0	1.1	0.42	2.0	1.9	3.1
		19/08/75	11.5	4.1	47.2	16.6	53.9				2.0	1.8	3.3
1261		17/08/75	12.2	5.6	68.3	1.2	12.3	16.6	3.8	0.80	2.0	5.9	19.0
1851	Δ 508	28/05/76	9.4	4.1	38.4	9.5	24.0	10.8	0.77	0.24	0.45	0.2	0.4
		30/05/76	16.0	4.1	65.6	0.9	7.5				0.50	0.08	0.2
		31/05/76	13.1	4.1	53.7	2.0	8.4				0.50	0.1	0.2
		03/02/77	12.1	4.1	49.7	14.4	51.1				1.2	0.7	1.4
1904		04/02/77	10.6	5.6	59.4	4.9	26.8	14.1	2.2	0.54	1.2	2.7	6.2
2298		04/06/76	-	5.6	-	-	4.9	12.2	3.1	0.88	2.0	-	6.4
3201		03/02/77	14.4	4.1	59.0	1.7	9.0	4.3	2.8	2.2	2.2	1.3	2.9
4147		20/05/76	-	5.6	-	-	0.9	18.6	2.42	0.45	2.0	-	3.0
		24/05/76	-	5.6	-	-	0.5						2.1
4372		05/02/77	33::	5.6	100::	-	2.4				1.2		
4590		04/02/77	11.5:	5.6	64.4:	1.0	7.8	8.9	3.6	1.4	1.4	1.9	5.2
5139*	Cen	19/05/76	7.2	4.1	29.4	30.7	63.2	5.4	7.6	4.8	2.0	65.3	93.7

TABLE 1 (continued)

Cluster NGC	Other	Date (D/M/Y)	D_a (%)	R	D (%)	C_1 (s^{-1})	C_2	d (kpc)	D_c (pc)	θ_c (arc minutes)	θ'	M_1 (solar masses)	M_2
5694*		20/08/75	19.5:	5.6	100:	0.0:	12.3	31.2	2.3	0.26	1.2	-	10.0
		21/08/75	14.6:	5.6	82:	0.0:	6.9				1.2	-	7.5
		28/05/76	16.7:	5.6	93:	0.0:	5.7				1.2	-	6.8
5824		22/08/75	8.0	5.6	44.7	6.3	18.8	23.2	0.85	0.13	0.45	0.4	0.8
5927		31/05/76	11.6	5.6	65.0	2.0	15.5	7.7	2.3	1.0	2.0	1.7	4.6
6121	M4	16/08/75	10.2	5.6	57.1	5.1	24.5	2.1	2.0	3.3	2.0	1.0	2.1
6218	M12	15/08/75	7.8	5.6	43.4	4.0	11.6	5.9	3.1	1.8	2.0	2.8	4.8
6266	M62	18/08/75	7.9	5.6	44.0	22.4	66.1	8.1	1.2	0.52	2.0	2.1	3.8
		19/08/75	10.9	5.6	60.9	11.7	68.1				2.0	1.6	3.8
		19/05/76	9.2	5.6	51.4	15.6	58.8				2.0	1.8	3.5
6273	M19	24/05/76	5.6	5.6	31.4	10.9	23.3	10.2	3.4	1.2	2.0	9.2	13.4
6333	M9	04/06/76	10.5	4.1	43.1	3.3	9.5	6.3	1.5	0.82	2.0	0.9	1.5
6362	Δ 225	03/08/76	12.8	5.6	71.7	0.7	11.3	7.8	7.3	3.2	1.21	8.9	35.9
6397	Δ 366	17/08/75	9.5	5.6	53.1	10.7	43.2	2.3	0.83	1.2	2.0	0.2	0.5
6441*		30/05/76	8.6	5.6	48.3	3.4	11.6	8.7	0.8	0.3	0.50	0.1	0.2
6544		02/09/75	11.5	5.6	64.2	2.65	19.2	4.2:	-	-	2.0		
6624*		30/05/76	15.8	5.6	88.5	0.0	4.6	6.3	0.61	0.33	0.5	-	0.07
		31/05/76	15.9	5.6	89.1	0.0	4.4				0.5	-	0.06
6637	M69	03/09/75	10.0	5.6	56.4	6.7	31.0	10.7	2.1	0.68	2.0	3.7	7.9
6681*	M70	22/08/75	13.0	4.1	53.5	5.6	23.0	11.3	0.67	0.20	1.21	0.4	0.8
6809	M55	16/08/75	7.8	5.6	43.5	3.5	10.3	6.3	6.4	3.5	2.0	14.5	24.9
6981	M72	03/08/76	9.3	5.6	52.1	2.1	8.1	17.1	5.7	1.1	1.2	8.9	17.4
7078*	M15	28/05/76	11.7	4.1	48.0	6.1	20.5	9.8	1.3	0.47	0.45	0.4	0.7

NOTES TO TABLE 1

* The definitions of the symbols used in this table are given fully in Paper I. Briefly, D_a is the apparent depth of the Hα line; R is the factor that accounts for the effect of overlapping orders; D is the true depth of the line; C_1 is the maximum count rate attributable to ionized hydrogen based upon an assumed line depth for the integrated spectrum of the underlying stars; C_2 is the count rate at the adopted continuum level; d is the cluster distance; D_C is the linear diameter of the core radius; θ_c is the angular diameter of the core; θ' is the aperture diameter used for observing; and M_1 and M_2 are the probable and conservative upper limits placed on the presence of ionized hydrogen in the clusters we have observed by use of C_1 and C_2, respectively. Distances and core diameters are taken from the list of Peterson and King (1975) updated to 1976 Dec. by Peterson (1977), except for NGC 104 and 6441 (Paper I values used here) and NGC 5694 (distance from Harris 1976). Clusters whose NGC numbers are labeled with an asterisk were also observed for Paper I. Notes specific to individual clusters follow:

NGC 104: "North" refers to a position 84″ north of the cluster center. No position overlap occurred between the measures of the cluster center and the north position.

NGC 121: Core diameter estimate by Peterson (1977) of a CTIO 4 m plate taken by J.E.H. The very weak NGC 121 Fabry-Perot data suggest a velocity of $+145$ km s^{-1} that is consistent, within the errors, with the other (also imprecise) measures. From a Radcliffe Newtonian spectrogram Kinman (private communication; see Thackeray 1959) reported a velocity, $+86$ km s^{-1}, that he considers to be of very low weight, serving only to show that it is consistent with membership in the SMC. A preliminary reduction of a narrow image-tube spectrogram from CTIO suggests 100 km s^{-1}.

NGC 1261: Photomultiplier voltage lower than used for other observations.

NGC 1851: The 1976 observations were obtained at extreme hour angles; radial velocity agreement with V_{MK} is excellent.

NGC 5694: Reductions of two additional spectrograms fully support the conclusions of Harris and Hesser (1976).

NGC 5824: V_{MK} based on individual values with a range of 78 km s^{-1}.

NGC 6218: Mayall (1946) reports $V = +36$ km s^{-1}, whereas the value most frequently quoted in the literature, -16 km s^{-1}, is a misprint in Kinman's (1959) compilation; Dr. Kinman informs us that no change in Mayall's value was intended. The interferometric data suggest either -50 or $+100$ km s^{-1}; independent spectrographic observations are being secured.

NGC 6441: See text, § II.

NGC 6637: V_{MK} based on individual values with a range of 119 km s^{-1}.

NGC 6981: Mayall (1946) obtained -274 km s^{-1}, but formed a weighted mean with Humason's (1934) value of -255 km s^{-1}; our preliminary interferometric value is ~ -286 km s^{-1}.

tain independent spectroscopic clarification of the discrepancies, we continue our conservative policy adopted in Paper I of assuming that the minima in the interferometer output correspond to absorption. Our detailed radial-velocity results will be presented when final analysis is completed.

III. IONIZED GAS

Our interferometric observations employed both the 91 cm and 1.5 m telescopes, and were taken as described in Paper I. Careful sky observations were obtained so that subtraction of galactic and geocoronal Hα emission could be made prior to evaluating the data for emission intrinsic to the clusters. Cluster selection was generally weighted toward the X-ray and brighter objects. The data are summarized in Table 1, whose format is the same as its counterpart in Paper I. Since the single most important assumption for setting upper limits via this technique is that of the volume over which the gas is distributed, clusters with large core volumes (e.g., NGC 121 or 5139) yield limits proportionally higher than those of other clusters.

The new and improved limits on ionized gas in the clusters NGC 1851, 6441, 6624, and 7078—i.e., those of our sample commonly associated with X-ray sources—are of particular interest for comparison with the class of models requiring mass infall onto a massive central black hole to generate the high-energy radiation (Bahcall and Ostriker 1976; Silk and Aarons 1976). (It should be noted, however, that our experiment would be insensitive to a short-duration, high-velocity [relative to the cluster] Hα flare such as that reported by Grindlay and Liller [1976; see also Margon *et al.* 1976] for NGC 6624).

Theoretical models (e.g., Scott and Rose 1975; Tayler and Wood 1975; VandenBerg and Faulkner 1977) suggest that gas will accumulate preferentially in the volume internal to the core radius (King 1962, 1966), where the escape velocity is highest. One of the assumptions required (cf. Paper I) to obtain the M_1 values of Table 1 is that the *intrinsic* depth of the line profile appropriate to the integrated spectra of globular clusters at Hα be known. That assumption can largely be removed for a few favorable objects such as NGC 104 (47 Tuc), where the line profile can be measured in the cluster halo and compared to that of the central regions. From measurements made with the 1.5 m telescope on 1976 August 21 and 22 (cf. Table 1), we find that, apart from a small systematic velocity shift consistent with rotation of the cluster as a whole, there is no difference in line profile between the core and halo samples; i.e., with respect to a halo region, there does not appear to be any appreciable Hα emission in a comparable core sample of 47 Tuc. Integration over the velocity range of the Hα absorption line in the difference spectrum suggests that roughly comparable volumes of halo and core in 47 Tuc differ in their ionized hydrogen content by $<0.03\ M_\odot$.

IV. CONCLUSIONS

1. Upper limits on ionized hydrogen gas have been set for 31 globular clusters. To date we have observed 48 clusters in a consistent manner, all of which have yielded null results.

2. Among the clusters for which the most stringent upper limits, $M_{\rm H\,II} < 1\ M_\odot$, have been placed on ionized hydrogen are four that are thought to be associated with X-ray sources: NGC 1851, 6441, 6624, and 7078.

3. A sensitive comparison of the core and halo regions of NGC 104 detects no differences in their line profiles attributable to ionized gas; this in turn implies that $<0.03\ M_\odot$ of ionized hydrogen gas is present in the core of 47 Tuc relative to a comparable volume of its halo.

4. The radial velocity of NGC 6441 is $\sim+13$ km s^{-1}, not -70 km s^{-1} as reported earlier (Mayall 1946).

It seems an inescapable conclusion of the combined observational efforts that the mass of interstellar matter expected to accumulate in globular star clusters as a natural consequence of stellar evolutionary processes is not present in the amounts predicted by the best available theoretical models. Unless the mass loss rates are considerably overestimated, or unless it can be shown that the material is present in some state to which the experiments conducted to date are insensitive, its removal by some means must be invoked. Scott and Rose (1975) have postulated that photoionization by ultraviolet light acts as a source of heating internal to the cluster. Recently Lea and De Young (1976) and Frank and Gisler (1976) have proposed that ram pressure acting on clusters moving at $\sim$100 km s^{-1} through a galactic halo of gas density 10^{-3} cm^{-3} would probably be sufficient to strip stellar ejecta from them; while such densities seem to be consistent with present interpretations of the interstellar lines of distant, high-galactic-latitude stars (Cohen 1975; Cohen and Meloy 1975), they are about an order of magnitude larger than those postulated two decades ago by Spitzer (1956) or more recently by Silk (1974) for the galactic halo. VandenBerg and Faulkner (1977) agree that a halo density of $\sim10^{-3}$ cm^{-3} would be required for ram pressure to be effective, but they argue that, even then, many of the most tightly bound clusters will retain their gas.

Clearly the gap between observation and theory of interstellar matter in globular clusters remains wide in spite of considerable progress in the last year. More comprehensive, quantitative observational evidence for mass loss from the stars themselves would be an invaluable contribution to this problem.

We gratefully thank K. Czuia, B. Grundseth, D. Maturana, C. Poblete, J. Ríos, O. Saá, and R. Venegas for their outstanding cooperation at the telescope; D. A. VandenBerg, G. Illingworth, and T. D. Kinman for communicating important new results and comments to us; A. P. Cowley, D. Crampton, F. D. A. Hartwick, and J. B. Hutchings for discussions and for making the Arcturus measuring engine available to J. E. H.; V. M. Blanco, B. J. Bok, J. A. Graham, B. M. Lasker, C. J. Peterson, M. G. Smith, and S. van den Bergh for stimulating comments on the present manuscript; R. Oliver for help with computing problems; and the University of Kansas General Research Fund for partial financial support of S. J. S.

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