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AN OPTICAL SEARCH FOR IONIZED HYDROGEN IN GLOBULAR CLUSTERS

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ABSTRACT

An attempt has been made to detect Hα emission from ionized gas in 26 globular clusters using a single-etalon, photoelectric Fabry-Perot interferometer. Assuming in each case that any ionized gas present is confined to the core, probable upper limits of the order of a few solar masses of ionized hydrogen have been derived. The clusters observed include many of those recently discussed by Bahcall and Ostriker, Scott and Rose, and Tayler and Wood.

Subject headings: clusters: globular — interstellar: matter — stars: mass loss

I. INTRODUCTION

The potentially important problems in stellar evolution presented by the failure to observe hydrogen gas lost from stars in globular clusters—in either neutral or ionized form—are now well known (e.g., Hills and Klein 1973; Knapp, Rose, and Kerr 1973; Scott and Rose 1975; Tayler and Wood 1975). Briefly the masses of horizontal-branch stars are thought to be ~ 0.5–$0.7\ M_\odot$ (e.g., Iben 1971). According to theories of stellar evolution (e.g., Iben 1967), stars of 0.5–$0.7\ M_\odot$ would require $\sim 20 \times 10^9$ years to evolve at constant mass to the tip of the red-giant branch; this is slightly longer than the age of the universe derived from the Hubble parameter (Sandage and Tammann 1975) and a deceleration parameter of zero. Mass loss can be postulated in order to increase the original masses of the progenitors of the horizontal branch, and hence make their rate of evolution sufficiently rapid. Woolf (1974) has reviewed the available observational evidence for mass loss, while Mäckle *et al.* (1975) have recently presented data which suggest that substantial mass loss may occur even before a star makes its final turn down to the horizontal branch. This gas may be expected to accumulate in the globular clusters, at least between their passages through the galactic plane (e.g., Idlis and Nikol'skii 1959; Roberts 1960; Hills and Klein 1973).

Recent observational approaches to the problem have been made mainly with radio telescopes.[1] Typical upper limits of $\sim 10\ M_\odot$ for the accumulated mass of neutral hydrogen have been set by Knapp, Rose, and Kerr (1973), while in four globular clusters upper limits of 0.4–$0.8\ M_\odot$ of neutral hydrogen have been set by Conklin and Kimble (1974). Hills and Klein (1973) set limits of typically 20–$40\ M_\odot$ for the mass of *ionized* hydrogen accumulated in globular clusters. Generally less sensitive limits for the ionized gas have been set in a wider sample of clusters by Erkes and Philip (1975), though in the case of M71 they derived an upper limit of $9\ M_\odot$.

On the theoretical side, Tayler and Wood (1975) have estimated that about $10^2\ M_\odot$ of gas should have accumulated in the $\sim 10^8$ years since the last passage of a typical globular cluster through the galactic plane. To reconcile this theoretical lower limit with the observational upper limits, they point out that one must assume that either (i) the mass loss per star is less than $0.2\ M_\odot$ (we have already discussed some of the problems associated with an assumption of negligible mass loss) or (ii) the gas is removed from the cluster or (iii) the gas is still in the cluster, but in some unrecognized form. Various theoretical approaches to the last two assumptions have been discussed recently (some of which are of particular interest to us as they make specific untested predictions regarding the mass of accumulated gas). Among them are the following:

a) Ejection from the cluster by a stellar-wind phenomenon (Scott and Rose 1975). With this model they predict an observable mass of ionized gas in NGC 6388. NGC 6441, which like NGC 6388 is highly condensed (concentration class III), massive (Illingworth 1973), and metal-rich (Hesser and Hartwick

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[1] Optical studies include investigations of nonuniformities in the stellar density distribution, which may or may not provide evidence for dust clouds in globular clusters (see, e.g., Idlis and Nikol'skii 1959; Hogg 1959; Roberts 1960; Hodge 1960; Gascoigne 1966). In the infrared, only a few exploratory measurements seeking emission from spatially extensive dust clouds have been reported (see, e.g., MacGregor, Phillips, and Selby 1973; Hansen and Hesser 1975), while two IRC sources have been linked with stars in the globular clusters M22 (Cohen 1971) and Terzan 5 (Warner and Wing 1971; Wing, Warner, and Smith 1973).

1976), should also have detectable gas (Scott, personal communication).

b) Condensation into stars (Roberts 1960; Johnson 1975) may be responsible for the presence of luminous "blue straggler" stars above and blueward of the main-sequence turnoff point in some globular clusters.

c) Accretion onto a massive central black hole (e.g., Bahcall and Ostriker 1975; Tayler and Wood 1975). The former authors, in their discussion of this potential mechanism for producing X-ray emission from globular clusters, have predicted an Hβ flux $F(\mathrm{H}\beta) \simeq 2 \times 10^{-11} d^{-2}$ ergs cm^{-2} s^{-1} from ionized gas in such clusters (where d is the distance to the cluster in kiloparsecs). They suggest nine specific candidates which they expect to be bound tightly enough to retain gas.

In discussing the possibility of modifying the estimates of the mass-loss rate, Tayler and Wood (1975) state, "Lower observational limits for the gas content, in particular for ionized hydrogen, are required before a quantitative estimate of the necessary reduction . . . can be made." Knapp, Rose, and Kerr (1973) have suggested that (Balmer) Hα observations should be able to set more sensitive limits on the amount of ionized gas than the radio continuum observations mentioned above. Bahcall and Ostriker (1975) also express "great interest" in searching for Balmer emission lines from the cluster centers. It is principally to these suggestions that we address ourselves in this paper. In particular, by observing the (Balmer) Hα line from each cluster we set probable upper limits of a few solar masses of ionized gas in seven of the nine clusters selected by Bahcall and Ostriker, four of the eight specifically mentioned by Tayler and Wood, as well as NGC 6388.

II. EQUIPMENT

The AURA, single-etalon, Fabry-Perot interferometer (Smith and Weedman 1971; Smith 1973), attached to the 91 cm telescope at Cerro Tololo was used in 1974 and 1975 for our globular cluster measurements. Most observations were made through Hα premonochromating filters having 14 and 17 Å nominal passbands centered $\sim$3 Å above and below the Hα line, respectively; the filter most appropriate to the velocity of the cluster being observed was selected in each case. A few trial observations with a 14 Å passband filter centered on the 5007 Å line of [O III] were made with the hope of avoiding prominent absorption-line features (as discussed in the Appendix, § *d*). All line-profile observations were made using an entrance aperture of 120″ in a manner similar to that described by Smith and Weedman (1971). The free spectral range (Vaughan 1967) was $Q = 3.365$ Å ($\sim$154 km s^{-1} at Hα), and each scan covered two complete orders divided into 150 data bins; each bin was sampled for $\sim$1 s per scan. In most cases, a series of scans were made alternating between the object, different sky positions, and a hydrogen calibration lamp; such individual scans of object and sky were combined later in the computer. The total time per data bin for each cluster was usually about 50 s.

III. OBSERVATIONS OF GLOBULAR CLUSTERS

a) *Line Profiles*

Emission from ionized hydrogen gas in a globular cluster would be readily detected with our technique of measuring the integrated light at Hα if this emission were concentrated in a line of width $\geqslant$0.1 Å, but relatively narrow compared to the underlying absorption. However, we have not seen an unambiguous emission feature in the data from any of the clusters; we have therefore had to resort to an analysis of any possible filling in of Hα absorption by latent emission. In the Appendix we discuss the assumptions we have had to make as a result of our lack of knowledge of either (i) the detailed form of the underlying absorption profile from the integrated stellar spectrum or (ii) the form of the superimposed emission feature (for three clusters, as discussed in § III*b*, further assumptions have been made about their radial velocities). However, *by far the most important assumption we have made is that any gas present in a globular cluster will be distributed uniformly over the volume defined by the core radius of the cluster* (see Appendix § *g*), an assumption compatible with the theoretical models mentioned in the introduction.

The data obtained in this study, typical examples of which are presented in Figure 1, are summarized in Table 1, where we give both the observed count rates (see explanation given in Appendix § *e*) and the physical parameters (distance, core diameters, etc.) necessary to obtain the upper limits for the mass of ionized hydrogen using equation (A5) (in Appendix § *g*). In general, these cluster parameters have been taken from the compilations by Peterson and King (1973, 1975); exceptions are noted in the footnotes to the table. Also included in Table 1 are two different estimates for the upper limit to the mass of ionized hydrogen (M_1 "probable" and M_2 "conservative") for each cluster (see Appendix § *e*). Blank entries for M_1 are explained in § III*b*.

b) *Radial Velocities*

As shown in Figure 1, the interferometer output is modulated in a periodic fashion by either emission or absorption features, with a spacing of $\sim$154 km s^{-1} between adjacent Hα interference orders (for a more detailed account of Fabry-Perot interferometers, see, e.g., Vaughan 1967). With broad features, one cannot state *a priori* whether it is emission or absorption which causes the observed modulation; radial velocities of the clusters are needed (to within 50 km s^{-1}) to point out the part of the interferometer output to be attributed to absorption or emission from the cluster. In every case except NGC 6522, velocities have been obtained by Mayall (1946) and/or Kinman (1959). For 18 of the 26 clusters, the Mayall/Kinman (V_{MK}) velocities point to the *minima* of the interferometer output to well within 50 km s^{-1}; for these 18, Hα has therefore been found in absorption.

We now discuss the remaining eight clusters. The signal-to-noise ratio for four of these (NGC 4590, 5694, 5824, and 6681) was insufficient for definite

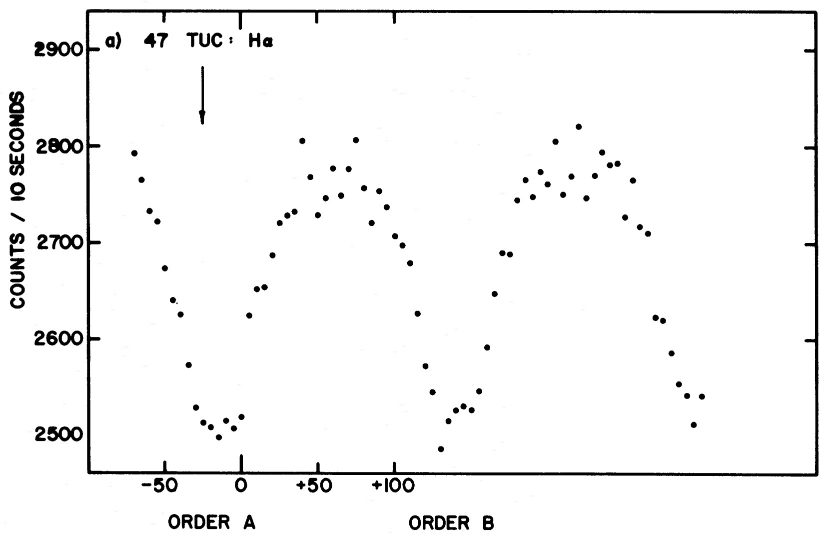

FIG. 1*a*

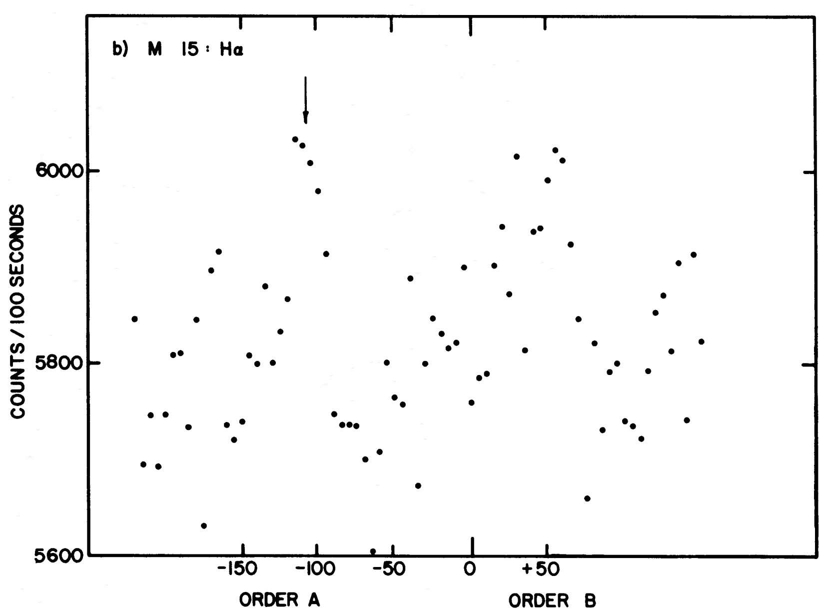

FIG. 1*b*

FIG. 1.—Interferometer line profiles for: (*a*) Hα absorption in 47 Tucanae—see Appendix § *e*; (*b*) Hα emission in M15—see Appendix § *h*; (*c*) [O III] λ5007 emission in M15—see Appendix § *h*; (*d*) data for NGC 6441—see § III*b*; and (*e*) Hα absorption in NGC 6388—see § IV. Data from pairs of adjacent data bins have been combined in these plots; thus each point represents ~10 s of observing time in (*a*) and ~100 s in (*b*)–(*e*). Sky subtraction has been performed for (*d*) and (*e*) only. Just over two interference orders are shown in each case. The velocity scale refers to order A, and an arrow on each graph indicates, for order A, the radial velocity determined by Mayall or Kinman.

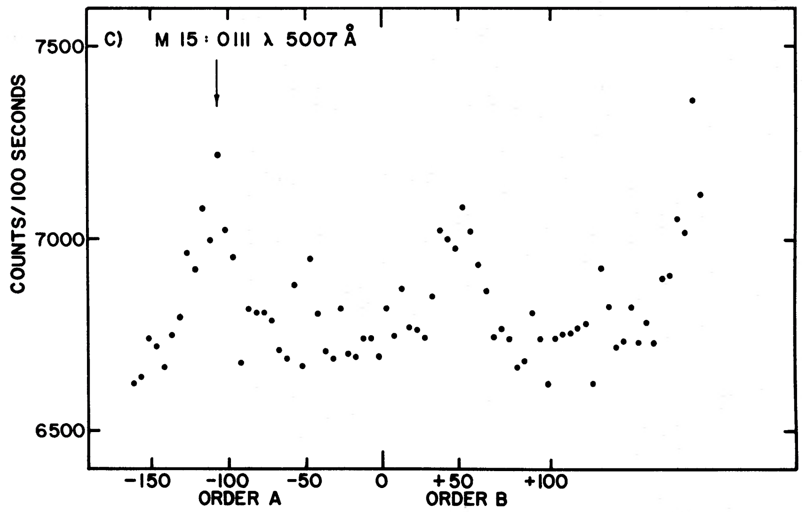

FIG. 1*c*

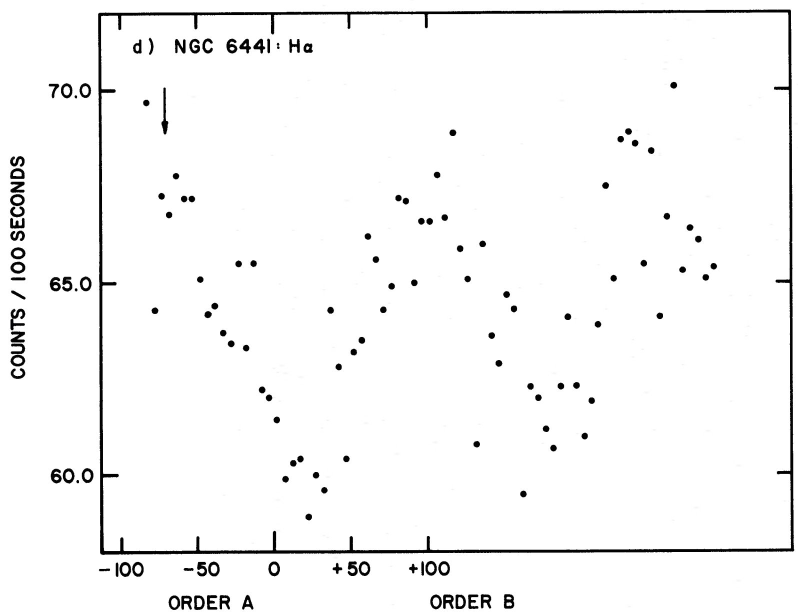

FIG. 1*d*

FIG. 1.—*Continued*

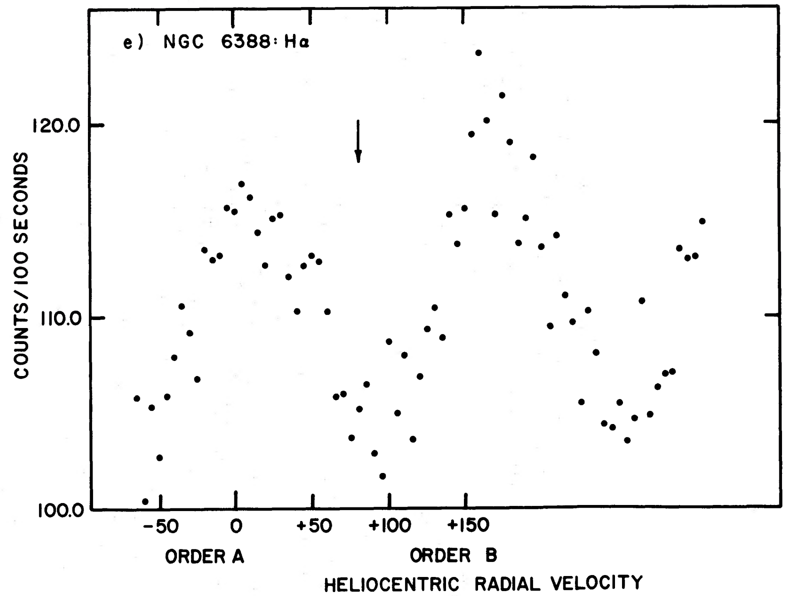

FIG. 1e

FIG. 1.—*Continued*

detection of the characteristic periodic modulation in the output data, so only the upper mass limit, M_2, is given in Table 1 for these cases. For NGC 6522 a V_{MK} is unavailable, but Kukarkin (1974) lists a velocity of -24 km s^{-1}; using that velocity for order selection, the interferometrically derived (absorption-line) velocity is -25 km s^{-1}. In the case of NGC 5986, Mayall's (1946) data point somewhere between the maxima and minima of the interferometer output; however, in this case, the internal scatter in his data is large (± 88 km s^{-1} rms). Therefore, for this cluster we have *assumed*, pending the results of further radial velocity studies, that the modulation of the interferometer output is produced by Hα absorption.

In the two remaining clusters, NGC 6441 and NGC 6723, the V_{MK} values (which have low internal dispersion) point to the maxima of the interferometer output. Taken at face value, this would indicate the detection of broad emission lines in these clusters. However, a single, low-quality, image-tube spectrogram of NGC 6441 taken with the new spectrograph on the 1.0 m (Yale) telescope on Tololo yields a heliocentric velocity of $\sim +54$ km s^{-1}, which we regard as consistent with the velocity[2] ($+16 \pm 16$ km s^{-1}) derived from the *minima* of the interferometer output (cf. Fig. 1). We have tentatively *assumed* that the modulation of the interferometer output for NGC 6441 is produced by Hα in absorption. Mayall (1946) found the radial velocity of NGC 6723 to be -3 km s^{-1} from spectrographic measures with low internal velocity dispersion. The interferometric absorption-line velocity nearest to the Lick value would be $+56$ or -98 km s^{-1}; we have been unable to secure independent spectrographic data. Pending further checks on the radial velocity of NGC 6723, we have again *assumed* in Table 1 that the modulation of the interferometer output, like that of other clusters observed is produced by Hα in absorption rather than in emission.

In summary, we have found that accurate radial velocities are derivable from the interferometric data on the Hα absorption line from the integrated spectrum of the globular clusters. Nevertheless, three ambiguous cases have arisen, namely, for NGC 5986, NGC 6441, and NGC 6723; for these we have chosen to make the more conservative *assumption* that Hα is in absorption, not emission, until their radial velocities (V_{MK}) can be independently verified. A future paper will present and discuss the interferometrically determined radial velocities in detail.

[2] The stability of the interferometer to shifts as extreme as half an order ($\sim$77 km s^{-1}) is not questioned because hydrogen-lamp scans taken before and after the observations of both clusters show relative displacements equivalent to $\lesssim 2$ km s^{-1} in all cases. Furthermore, the interferometer observations of NGC 6441 taken on widely differing dates agree to well within the expected uncertainties ($\sim$16 km s^{-1}).

IV. DISCUSSION AND CONCLUSIONS

We begin this section by briefly commenting on how our data bear upon the models discussed in the Introduction. In Table 2 we compare the observed upper limits M_2 (the more conservative) with the masses predicted by Tayler and Wood (1975) for the clusters in common. If both (i) their arguments apply to the clusters in question and (ii) our assumptions made in the derivation of equation (A5) are valid, then our data provide significant support for their conclusion that modifications have to be made in existing models of the structure and evolution of horizontal-branch and RR Lyrae stars.

A comparison is made in Table 3 of the observed fluxes (F_1 and F_2) with those predicted by Bahcall and

TABLE 1*

Results from Interferometrically-Measured Hα Line Profiles for Globular Clusters

Cluster		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)
NGC 104	47 Tuc	04/08/74	10.4	5.6	58.2	53.6	270.5	4.9	1.4	1.0	2.0	2.6	5.8
								4.0	1.0	0.95	2.0	1.3	2.9
NGC 2808		09/05/75	10.1	5.6	56.6	14.0	65.5	7.2	1.4	0.7	2.0	1.9	4.2
NGC 3201	Δ 445	12/06/75	-	-	-	-	9.6	4.3	2.8	2.2	2.2	0.9:	2.7
		14/06/75	15.1	4.1	61.9	1.0:	6.1						
NGC 4590	M68	01/06/75	-	-	-	-	4.3	8.9	3.6	1.4	2.0	-	5.5
NGC 4833		19/06/75	14.2	5.6	79.5	0:	14.5	5.0	3.4	2.3	2.3	1.5	5.9
		21/06/75	10.9	5.6	61.0	2.3	13.7						
NGC 5024	M53	15/06/75	12.9	5.6	72.2	0.5	9.3	20.0	5.4	0.9	2.0	7.7	33
NGC 5139	ω Cen	18/05/74	10.3	4.1	42.2	18.0	50.4	5.4	7.6	4.8	4.8	58	92
		06/08/74	8.5	4.1	34.9	30.6	71.0						
NGC 5286	Δ 388	22/06/75	8.7	5.6	48.7	6.1	20.7	8.7	1.6	0.6	2.0	1.9	3.5
NGC 5694		28/06/75	-	-	-	-	2.0	24.3	1.8	0.3	2.0	-	3.6
NGC 5824		11/05/75	-	-	-	-	6.0	18.3	0.6	0.1	2.0	-	0.9
NGC 5904	M5	26/05/74	10.8	5.6	60.5	10.1	57.6	8.2	2.2	0.9	2.0	3.7	8.8
NGC 5986	Δ 552	30/06/75	10.8	5.6	60.5	2.9	16.6	9.8	3.0	1.1	2.0	3.8	9.0
NGC 6093	M80	02/06/75	10.8	5.6	60.5	4.1	23.5	7.3	0.4	0.2	2.0	0.1	0.4
		12/06/75	11.7	5.6	65.5	2.6	20.6		0.7	0.3	2.0	0.3	0.9
NGC 6388		09/05/75	14.5	5.6	81.2	0:	53.6	13.8	1.2	0.3	2.0	1.8	5.9
		21/06/75	10.8:	5.6	60.5:	10.3:	59:						
NGC 6441		02/06/75	9.5	5.6	53	8.4	33.6	8.7	0.8	0.3	2.0	0.8	1.6
		27/06/75	9.8	5.6	55	7.7	33.5						
NGC 6522		21/06/75	13.6:	5.6	76.2:	0.2:	11.8	7.3	0.6	0.3	2.0	0.1	0.5
NGC 6541		13/06/75	9.6	5.6	53.8	0.5	27.0	6.2	1.2	0.7	2.0	0.9	1.8
NGC 6624		15/06/75	13.3	5.6	74.5	0.4	12.8	4.8	0.5	0.4	2.0	0.05	0.3
NGC 6626	M28	30/06/75	10.2	5.6	57.1	6.4	30.5	4.0	0.8	0.7	2.0	0.3	0.7
NGC 6681	M70	22/06/75	-	-	-	-	9.5	12.0	0.7	0.2	2.0	-	0.9
NGC 6715	M54	20/06/75	11.2	5.6	62.7	3.8	24.9	13.7	1.2	0.3	2.0	1.5	3.9
									1.1	0.3	2.0	1.3	3.4
NGC 6723	Δ 573	27/06/75	12.9	5.6	72.2	0.9	16.3	10.5	4.8	1.6	2.0	4.5	19
NGC 6752	Δ 295	11/05/75	14.0	5.6	78.4	0:	44.9	5.0	1.4	1.0	2.0	-	2.4
NGC 6864	M75	28/06/75	11.3	5.6	63.3	1.6	10.6	25.1	1.8	0.2	2.0	3.3	8.6
									1.6	0.2	2.0	2.8	7.2
NGC 7078	M15	06/08/74	Emission	5.6	Emission	- see text	-	10.0	1.4	0.5	2.0	- see text	-
		12/06/75	8.7	5.6	48.7	7.4	25.4					2.0	3.6
NGC 7099	M30	14/06/75	11.6	5.6	65.0	1.5	11.2	8.7	0.6	0.2	2.0	0.2	0.6

* The definition of the symbols used in this table are given in Appendix sections (a), (e), and (g). Distances and core diameters are taken from Peterson and King (1975), except where noted below.

NOTES TO TABLE 1

NGC 104. Second distance estimate from Hartwick and Hesser (1974). Second estimate of core diameter from Illingworth (1973). The angular diameter of the core is based on Hesser and Hartwick's (1976) modification of Illingworth's data. See Tables 2 and 3.

NGC 3201. The first observation was taken with insufficient signal-to-noise ratio to make a good measurement of the absorption features.

NGC 4590. Signal-to-noise ratio too low for reliable line-profile measurements.

NGC 5024. Mayall's velocity has an uncertainty (weighted rms error) of ± 45 km s^{-1}. Our observation is consistent with the assumption that one sees an absorption rather than emission line.

NGC 5139. The absorption line is very wide. The large derived mass limits arise from the very large core radius associated with ω Cen. See Table 2.

NGC 5286. Distance from Harris, Racine, and de Roux (1976). Angular diameter of core from Peterson and King (1973).

NGC 5694. Signal-to-noise ratio too low for reliable line-profile measurements.

NGC 5824. Signal-to-noise ratio too low for reliable line-profile measurements. See Table 3.

NGC 5904. Poor velocity agreement between V_{MK} and V_{CT}. Kinman gives a weighted mean velocity, based on measures by him, by Mayall (1946), and by Joy (1949) of $+49$ km s^{-1}, whereas we obtained $+74$ km s^{-1}. Moreover, Mayall's weighted mean velocity includes one highly discordant measure which, if omitted, yields an average radial velocity obtained from the low-dispersion Crossley plates of 77 $\pm$ 6 (s.e.) km s^{-1} and a weighted mean of 66.5 km s^{-1}. Nevertheless Edmonson (1935), Joy (1949), and Kinman (1959) all report velocities which are lower than either the revised results of Mayall or our value. See Table 2.

NGC 5986. Poor velocity agreement between V_{MK} and V_{CT}, as discussed in § III*b*.

NGC 6093. Second value of angular diameter from Illingworth (1973). See Table 3.

NGC 6388. Distance and core diameter from Illingworth (1973; see also Illingworth and Freeman 1974). Observed upper limits are much lower than predicted by Scott and Rose (1975).

NGC 6441. Poor velocity agreement between V_{MK} and V_{CT}, yet Mayall's (1946) velocities show low internal dispersion—see § III*b*. Distance from Hesser and Hartwick (1976). Angular diameter of core from Illingworth (1973).

NGC 6522. No V_{MK} exists—see § III*b*.

NGC 6541. See Table 3.

NGC 6624. Provisional distance estimate from Liller and Liller (1975, personal communication). Angular diameter of core from Peterson and King (1973).

NGC 6681. Signal-to-noise ratio too low for reliable line-profile measurements. Distance from Harris (1974). Angular diameter of core from Peterson and King (1973).

NGC 6715. Second estimate of core diameter from Illingworth (1973).

NGC 6723. Poor velocity agreement between V_{MK} and V_{CT}—see § III*b*.

NGC 6752. No measurements were made of nearby blank-sky regions; cluster is bright and the signal-to-noise ratio was high. See table 3.

NGC 6864. Second estimate of core diameter from Illingworth (1973).

NGC 7078. 1974 measure includes planetary nebula. 1975 measure excludes it but includes core. See Tables 2 and 3.

NGC 7099. See Table 3.

TABLE 2

COMPARISON WITH THE MODELS BY TAYLER AND WOOD (1975)

Cluster (NGC)	104	5139	5904	7078
Predicted mass ($M_\odot$) of accumulated gas:				
a) in 10^8 years	186	413	90.4	78.2
b) since crossing the plane	52.1	14.0	15.4	10.2
Observed mass of ionized hydrogen M_2	< 5.8	< 92	< 8.8	< 3.6
Observed mass of neutral hydrogen*	< 15	< 20	< 0.8	< 0.8

* Limits on mass of neutral hydrogen are from Robinson 1967 or Conklin and Kimble 1974.

Ostriker (1975) for clusters which they expect to be bound tightly enough to retain gas. (F_1 and F_2 correspond to the count rates C_1 and C_2, using the definitions in Appendix §§ *e* and *f*.) The present observations come close to providing a significant test, particularly in the case of NGC 6541. A larger telescope and narrower interference filter would improve our limits, for the cores of the clusters concerned all subtend angles much smaller than that subtended by the diaphragm of the interferometer.

Scott and Rose (1975) give, in their Table 1, an expected accumulated mass of 35.8 $M_\odot$ for NGC 6388 under the assumptions governing the model developed in their paper. However, from analysis of our data, a sample of which has been given in Figure 1, we derive upper limits[3] $M_1 = 1.8\ M_\odot$ and $M_2 = 5.9\ M_\odot$ for ionized hydrogen in the cluster. Unless the emission lines are sharper than about 0.1 Å (full width at half-maximum intensity—see Appendix § *f*), this discrepancy is likely to be significant. Their models would also predict (Scott, personal communication) a significant accumulation of gas in the similar massive (Illingworth 1973), and metal-rich (Hesser and Hartwick 1976) globular cluster NGC 6441. Pending further checks on the radial velocities (see § III*b*), it seems reasonable to *assume* (i) that here, too, we are observing Hα in absorption and (ii) that upper limits to the mass of ionized hydrogen of $M_1 = 0.8\ M_\odot$ and $M_2 = 1.6\ M_\odot$ have consequently been set by our observations.

This general situation clearly warrants further theoretical and observational effort. Four more or less conventional observational approaches come readily to mind: (*a*) Constraints on neutral and ionized hydrogen set by radio and optical observations must be tightened still further and extended to selected unstudied objects; e.g., there is a regrettable lack of radio observations for the more southerly globular clusters. (*b*) Direct plates with large scale are needed to investigate suspected obscuring patches of material in globular clusters (Idlis and Nikol'skii 1959; Roberts 1960); however, such a program must be followed by polarimetric, infrared, and classical studies for confirmation of the physical reality of the patches, which might represent the recycling of ejected material into the formation of a new generation of cluster stars. (*c*) Similarly, evidence from such photographs for statistically significant deviations in the observed stellar-density distribution function from that of an isothermal model might provide support for recent suggestions that new physical phenomena may be taking place in the cores of some globular clusters (Bahcall and Ostriker 1975; Quintana 1975, personal communication; Bahcall, Bahcall, and Weistrop 1975). (*d*) Spectroscopic[4] and photometric studies of

[3] There can be no doubt that the measured feature in the interferometer data for NGC 6388 is due to absorption and not emission. We have independently determined a radial velocity of $+77$ km s^{-1} for this cluster from three image-tube spectra at 125 Å mm^{-1}, each of which clearly shows Hα in absorption; the mean of the corresponding interferometric velocity determinations is 81 ± 7 km s^{-1}, in perfect accord with Mayall's (1946) mean value. If 35.8 $M_\odot$ of hydrogen were in fact collected in the core of the cluster and emitting according to the assumptions we have made, then strong emission features would have dominated the interferometer output.

[4] *Note added in proof.*—After submission of this paper, we learned that Cohen (1975) has reported narrow Hα emission features in the spectra of several of the brightest giants in the globular clusters M3, M13, and M92; she interprets the features as evidence for a circumstellar envelope produced by mass loss. The gas has a velocity sufficiently high that it may not be bound to the cluster, and the mass-loss rate agrees well with that expected from evolutionary calculations. Should future spectroscopic observations show the Hα emission phenomenon to be a general feature along the entire giant branch, then the present observations point to the need for re-evaluation of the importance of various mechanisms for removal of gas from globular clusters, and a consequent revision of the models discussed in the Introduction.

TABLE 3

COMPARISON WITH THE MODELS BY BAHCALL AND OSTRIKER (1975)

Cluster	Adopted Distance (kpc)	2.8 × Predicted $F(H\beta)$ (ergs cm^{-2} s^{-1} × 10^{-13})	Observed $F(H\alpha)$ (ergs cm^{-2} s^{-1} × 10^{-13}) F_1	F_2
NGC 104 (47 Tuc)	4.0	35	302	1353
NGC 5824	18.3	1.7	...	30
NGC 6093 (M80)	7.3	10	20	110
NGC 6541	6.2	90	36	135
NGC 6752	5.0	22	6.5	225
NGC 7078 (M15)	10.0	5.6	40	127
NGC 7099 (M30)	8.7	7.4	8.5	56

individual stars may also provide information concerning the importance of mass-loss phenomena in Population II systems. However, it seems to us that the apparent failure to detect ejected hydrogen gas by the rather conventional approaches followed until now justifies sensitive searches for less conventional signatures (soft X-rays, infrared emission, nebular emission lines, etc.). At the same time the most fruitful interplay between observation and theory requires that construction of theoretical models be vigorously pursued, in order to predict, with improved precision, the quantities and current physical conditions of any material ejected during the course of stellar evolution within a globular cluster.

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APPENDIX

Although we discuss the limitations of the instrument here in some detail, we shall see later that these usually do not affect the formal upper limits on the amount of ionized gas by more than a factor $\sim$2–3; thus *large uncertainties in the individual estimates made here for each instrumental effect produce relatively small changes in the derived upper limits.*

Essentially two problems must be solved before our data may be interpreted: (i) determination of the effect of the overlapping continua from neighboring interference orders on the observed depth of an absorption line; and (ii) the actual flux calibration of the instrument. The former is a problem that does not arise with the use of the interferometer on nebular emission-line objects; we have attempted to resolve it in a conservative manner by utilizing the known parameters of the monochromating filters as well as by stellar observations. For the flux calibration, observations of well-studied nebulae were obtained.

a) *Problems Associated with the Use of a Single-Etalon Instrument*

A single-etalon Fabry-Perot suffers from the problem that the continuum level measured consists of more than one overlapping order, as illustrated in Figure 2 (see also Vaughan 1967). For example, using the transmission

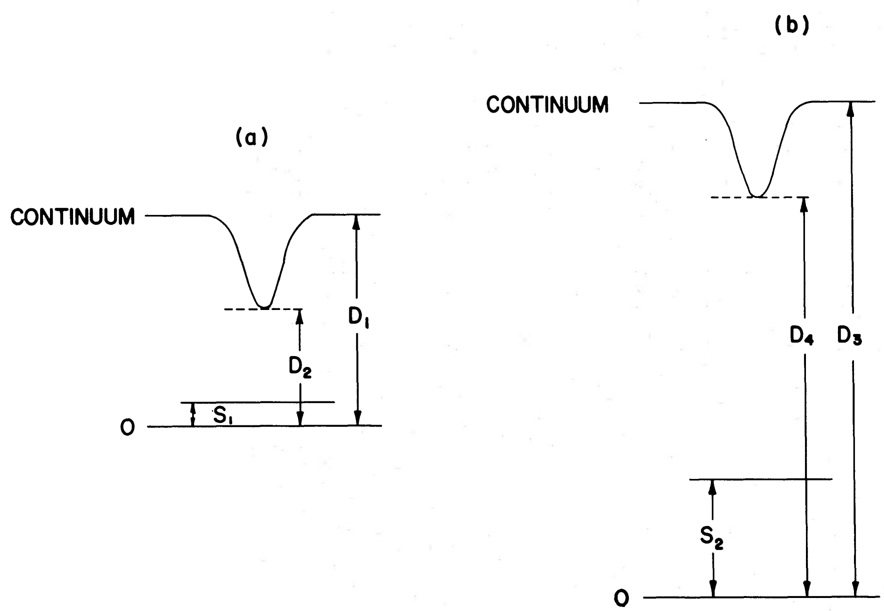

FIG. 2.—The effect of overlapping orders on the output of absorption-line data from a single-etalon interferometer. (*a*) The true absorption-line profile as it would be displayed by an interferometer having a perfect monochromating filter, i.e., one that passes only a single interference order. Its fractional depth referred to the continuum level is $D = (D_1 - D_2)/(D_1 - S_1)$. (*b*) In practice, the continuum from the source and sky is passed by the premonochromating filter into several neighboring interference orders; these additional orders overlap with the one containing the absorption line. Their effect is to raise the apparent level of the continuum and thereby decrease the apparent depth of the line, $D_a = (D_3 - D_4)/(D_3 - S_2)$. The correction factor, R, to convert apparent depths, D_a, to true depths, D $(D = RD_a)$, can be derived by observation of a standard star (Appendix § *a*). R is also the effective number of orders, D_3/D_1, passed by the interferometer, for $D_3 = RD_1$, $D_4 = (R - 1)D_1 + D_2$, $S_2 = RS_1$, and so $D_a = (RD_1 - RD_1 + D_1 - D_2)/R(D_1 - S_1) = D/R$ (ignoring the effects of neighboring absorption features as discussed in Appendix § *a*). Thus, R can also be determined from knowledge of the transmission characteristics of the filter.

curve for the 17 Å filter, it was estimated that a continuum level equivalent to $\sim$4.4 additional orders was added to the signal from the order containing the Hα absorption line (and any other absorption features in the strip of spectrum passed by the interference filter to the etalon). From Figure 2 it can be seen that, in the absence of absorption features other than Hα, the true depth, $D = (D_1 - D_2)/(D_1 - S_1)$, of an absorption line can be obtained by multiplying the displayed apparent depth, $D_a = (D_3 - D_4)/(D_3 - S_2) = DR^{-1}$, by a factor of R ($\sim$5.6 for the 17 Å filter), where R is the effective number of overlapping orders and S_1, S_2 are the background contributions in each case. However, the potential presence of nearby absorption lines makes this estimate uncertain. Any lines that overlap the Hα line (integral multiples of the free spectral range, Q, distant from the wavelength of Hα) will increase D_a. Those lines that do not overlap will reduce the level of the displayed continuum and may reduce the measured value of D_a if their effect cannot be seen clearly in the output display.

In order to make estimates of the filling-in of absorption lines by weak emission, it is clearly essential to derive the correction factors D/D_a for a star (or stars) that closely approximate the integrated stellar spectrum of the globular clusters to be observed. For this purpose we chose Arcturus (α Boo) because it is a bright K giant with low metal abundance (Griffin and Griffin 1967; van Paradijs and Meurs 1974; Mäckle *et al.* 1975) for which good spectrophotometric data (Griffin 1968) are also available for the Hα region. It is, however, somewhat later in spectral type than desirable. For Arcturus the derived and finally adopted values of D/D_a (with the 17 Å filters, 5.6, and with the 14 Å filter, 4.1) are in satisfactory agreement with the predictions from the transmission curves.

b) *Problems Associated with Lack of Knowledge of the Integrated Spectrum of the Stars in the Globular Cluster*

In an attempt to make rough estimates for the range of likely Hα absorption-line depths in the integrated stellar spectra of the globular clusters observed, we measured Hα profiles for six Population I giant and subgiant stars in the range G8–K5. The derived depths have a mean value of $D = 78 \pm 15$ percent (s.d.), in satisfactory agreement with the value derived directly from Griffin's (1968) tracings of Arcturus. However, a Population I F0 subgiant gave $D = 39$ percent. We conservatively adopt $D = 78$ percent as the intrinsic depth of the Hα absorption line in all the globular clusters, thereby ignoring effects such as variations of spectral type and metal abundances, and the reduced absorption-line depth in an integrated spectrum made up of stars of many different spectral types.

c) *Problems Associated with the Use of Point-Source Calibrations*

We have compared observations of extended sources against calibrations derived from point sources. For emission lines, theory (Flynn 1966) and practice (Bohuski and Smith, in preparation) show that while shifts up to $\sim$10 km s^{-1} in peak positions can occur when the uniformity of illumination changes, practically no effect is observed on the profile *shape*. Interferometer scans of the lunar Hα line were compared with the *Utrecht Solar Atlas* (Minnaert, Mulders, and Houtgast 1940); these confirm that any correction would be small, and as it is imprecisely known, we shall not attempt to include it in the subsequent discussion.

d) *Procedure Adopted*

The Hα lines observed in the globular clusters were almost always shallower than the 78 percent derived above from late-type stars. If we follow the conservative approach of *assuming that the apparent filling-in is entirely attributable to errors in the calibration*, then: (*a*) the appropriate value of D/D_a for a given cluster was always greater than the value of 5.6 derived for Arcturus; and/or (*b*) the assumed intrinsic depth of 78 percent is too great and our derived upper limits are, as expected, correspondingly too conservative.

The first potential source of error could be avoided by using a multi-etalon device (e.g., Mack *et al.* 1963; Meaburn 1972). The Hα lines from the six stars observed cannot have depths exceeding 100 percent, yet the mean observed value of $D_a \simeq 13.8$ percent; therefore, D/D_a cannot exceed $\sim$7.2 for the 17 Å filter (and will be less for the 14 Å filter).

The second potential source of error is intrinsic to all optical work on the Hα lines in globular clusters and has been discussed in § *b* of this Appendix. In ω Cen for instance, using the extreme value of $D/D_a = 7.2$ (even though the observations were made with the 14 Å filter), the derived depth is only 68 percent. In an attempt to avoid or reduce this second source of error (and thereby lower our derived limits) two approaches were tried. The first was to observe at λ5007 Å to look for [O III] emission from the interstellar gas. An absorption-line structure was found that varied markedly from cluster to cluster, making it impossible to fix a consistent background level from which to measure; however, [O III] observations with a multi-etalon device might be more successful. The second approach was to use interference-filter image-tube photography at the Cassegrain focus of the 1.0 m Yale telescope on Cerro Tololo. No obvious extended emission in either Hα or [O III] was detected, though quantitative measurements to set upper limits have not been attempted.[5]

[5] A third approach, applicable only to the brightest clusters, is a differential one in which observations made just outside the core radius are compared with observations of the core volume itself. The differential technique requires no *a priori* knowledge of the form of the intrinsic underlying absorption profile, provided it is similar in both the outer and inner regions. We plan to use this approach in attempts to lower our derived limits for selected objects.

e) The Tabulated Parameters D_a, D, C_1, C_2, M_1, and M_2

In order to clarify the definition of the central depth D, the count rates C_1 and C_2, and the estimated upper limits M_1 and M_2 for the mass of ionized hydrogen, given in Table 1, we provide an example using the data for 47 Tucanae. As shown in Figure 1*a*, the continuum level was observed to be ~ 279 counts s^{-1} (cps) while at the minimum of the absorption line the count rate was ~ 251 cps. The sky 30′ north of the cluster gave 8.0 cps before the observation of the cluster and 9.0 cps after, a mean of 8.5 cps (this includes the dark count of 1–2 cps). The apparent percentage depth is then $D_a = (279 - 251)/(279 - 8.5) = 10.4$ percent. The 17 Å filter was used, so the estimated absorption-line depth (from stars, filled in by any interstellar matter) is ~ 58 percent (see § *a* of this Appendix). An upper limit, C_1, to the counts from any ionized gas present can be obtained by assuming that the true depth of the line is 78 percent (see § *b*) and that $78 - 58 = 20$ percent of the line has been filled in by Hα emission. This would then correspond to a count rate of $C_1 = 0.20(279 - 8.5) = 54$ cps. A more conservative, much less probable upper limit (see § *d*), C_2, can be set by assuming that the true depth of the absorption line is 100 percent, while simultaneously ignoring the detection of the Hα absorption line. If such a line were completely filled in by ionized gas in 47 Tucanae, the count rate corresponding to this gas would be $C_2 = 1.00(279 - 8.5) = 270$ cps. By ignoring the detection of Hα absorption, *we are eliminating all uncertainties arising from the instrumental effects discussed so far* in this Appendix. Values of M_1 and M_2, corresponding to C_1 and C_2, respectively, have been calculated from equation (A5) to obtain the upper limits to the mass of gas given in Table 1. Using C_2 instead of C_1 generally results in mass estimates about 2 or 3 times larger. The significance of the limit M_2 is that—if the assumptions concerning line width (see § *f*), physical conditions, and central concentration of gas (see § *g*) are correct—any quantity of ionized hydrogen gas exceeding this limit should give rise to emission features above the continuum level in the interferometer output.

f) Flux Calibration

In order to calibrate the sensitivity of the equipment, observations were made of IC 418, NGC 1535, and NGC 7009, whose Hβ flux densities have been calibrated by Peimbert and Torres-Peimbert (1971) and by Liller (1955). The equipment had also been calibrated immediately following our first observing run by H. M. Johnson (1975, personal communication) through Perek's (1971) measurements of the Hβ flux, $F(\mathrm{H}\beta)$, from NGC 5189. The four calibration sources yielded the following relations between interferometer counts at the profile peak through a 2′ diaphragm, C, and flux density at Hα [taken as $F(\mathrm{H}\alpha) = 2.8F(\mathrm{H}\beta)$ which corresponds to an assumption of radiative case B de-excitation (Pengelly 1964)]:

$$\text{IC 418} \quad F(\mathrm{H}\alpha) = 4 \times 10^{-13} C \text{ ergs cm}^{-2}\,\text{s}^{-1};$$

$$\text{NGC 1535} \quad F(\mathrm{H}\alpha) = 6 \times 10^{-13} C \text{ ergs cm}^{-2}\,\text{s}^{-1};$$

$$\text{NGC 5189} \quad F(\mathrm{H}\alpha) = 5 \times 10^{-13} C \text{ ergs cm}^{-2}\,\text{s}^{-1};$$

$$\text{NGC 7009} \quad F(\mathrm{H}\alpha) = 7 \times 10^{-13} C \text{ ergs cm}^{-2}\,\text{s}^{-1}.$$

In spite of the reasonably close agreement among these values, the uncertainty in the flux at Hα is difficult to evaluate quantitatively because the instrument has not been extensively used in the past for *photometric* work and its properties for such work are therefore not reliably known. (Nevertheless, 12 measures of NGC 7009, each on different dates, showed a standard deviation of ~ 14 percent even without taking into account air mass or other factors necessary for precise photometric reductions).

Reasonably consistent results between the four calibrating sources were obtained because the emission-line profiles from each source were of similar shape and the area under each profile was approximately proportional to the profile height. For the globular clusters, the expected forms of the profiles of both the underlying Hα absorption line and the superposed emission line depend on the models adopted for the cluster and for the mass loss. Sharp emission cores were not obviously present in our observed absorption-line profiles, so we have assumed that any filling-in of the intrinsic absorption-line profile is produced by an emission feature having a width similar to the lines from the calibrating nebulae. (The Hα emission lines in the calibrating nebulae had profiles similar in shape and width to the Hα absorption lines observed in the globular clusters.) Let us suppose that the emission lines produced by ionized gas in the globular clusters are broader than those of the calibrating nebulae. In that case, the use of the reduction in the central depth of the absorption-line profile, with respect to its intrinsic value (as a measure of the total change in the area of the absorption-line profile produced by any latent emission) will tend to underestimate the emission flux. *In the absence of detailed models for the emission-line profiles, we have adopted the simplifying assumption that* $F(\mathrm{H}\alpha) \simeq 5 \times 10^{-13} C$ ergs cm^{-2} s^{-1}, where C is the apparent decrease in central depth of the Hα absorption feature in counts per second.

g) The Relation between Observed Quantities and the Mass of Ionized Hydrogen

We derive here the relation connecting the mass of ionized gas M required to give a count rate C. The following notation will be used in our derivations:

$L(\mathrm{H}\beta)$ = $\mathrm{H}\beta$ luminosity (in ergs s^{-1});
α_{4-2} = transition probability from level 4 to level 2 in the hydrogen atom;
h = Planck's constant (erg s);
ν = frequency of $\mathrm{H}\beta$ line (Hz);
N_e = electron number density (cm^{-3});
M = mass of ionized hydrogen in solar units;
V = volume (cm^3);
m_H = mass of hydrogen atom (g);
$L(\mathrm{H}\alpha)$ = $\mathrm{H}\alpha$ luminosity (ergs s^{-1});
$F(\mathrm{H}\alpha)$ = $\mathrm{H}\alpha$ flux density (ergs $\mathrm{cm}^{-2}\,\mathrm{s}^{-1}$);
d = distance to the globular cluster (kpc);
D_c = core diameter of the globular cluster (pc);
T_e = electron temperature of the ionized gas in the cluster (K);
θ = angular diameter of the volume occupied by gas in the globular cluster (arcmin).

From the definition of quantum emission rate by Pengelly (1964, eq. [34]),

$$L(\mathrm{H}\beta) = VN_e^2\alpha_{4-2}h\nu\,,$$

where $\alpha_{4-2}h\nu = 12.4 \times 10^{-26}$ corresponding to case B (i.e., a nebula optically thick to Lyman-line photons [Baker and Mezel 1938]) with $T_e = 10^4$ K.[6] Thus, assuming the gas is totally ionized,

$$M = m_\mathrm{H}N_eV = \frac{m_\mathrm{H}L(\mathrm{H}\beta)}{N_e\alpha_{4-2}h\nu}\,,$$

and therefore

$$M = 6.79 \times 10^{-33}L(\mathrm{H}\beta)/N_e \text{ solar masses}\,. \tag{A1}$$

Under case B conditions, radiative recombination should lead to an intrinsic ratio $L(\mathrm{H}\alpha)/L(\mathrm{H}\beta) = 2.8$ over a broad range of temperature (Pengelly 1964); under case A conditions, the ratio is ~ 2.7. If we *assume* case B radiative recombination, then equation (A1) can be rewritten as

$$M = 2.42 \times 10^{-33}L(\mathrm{H}\alpha)/N_e \text{ solar masses}\,. \tag{A2}$$

Now $L(\mathrm{H}\alpha) = F(\mathrm{H}\alpha)4\pi d^2(3.0856 \times 10^{21})^2$ ergs s^{-1} and $F(\mathrm{H}\alpha) \leqslant 5 \times 10^{-13}C$ ergs $\mathrm{cm}^{-2}\,\mathrm{s}^{-1}$, where C may be either C_1 or C_2 (see §§ *e* and *f*). $F(\mathrm{H}\alpha)$ is the total flux from the object, and it has been assumed that the object is wholly contained within the $2'$ interferometer diaphragm. If the volume of ionized gas has an angular diameter θ greater than $2'$ and has uniform surface brightness in $\mathrm{H}\alpha$, then $F(\mathrm{H}\alpha) \leqslant 5 \times 10^{-13}C(\theta^2/4)$ and

$$M \leqslant 3.62 \times 10^{-2}\frac{C\theta'^2d^2}{N_e} \text{ solar masses}\,, \tag{A3}$$

where $\theta' = 2'$ for values of $\theta \leqslant 2'$ and $\theta' = \theta$ for $\theta > 2'$. This expression is used in estimating the mass of ionized gas in the globular cluster M15 (§ *h*).

In order to estimate N_e *we assume that the gas is distributed uniformly through the cluster out to the core radius*, r_c. This is the most critical assumption in our paper; uncertainties in the final limits derived are governed almost entirely by the validity of this assumption and of that regarding the shape of the emission-line profile (cf. § *f*). The thermal velocity of the ionized gas, $(3kT/m_\mathrm{H})^{1/2}$, is about 16 km s^{-1} (if $T_e = 10^4$ K), which is comparable to the mean escape velocity for many clusters (e.g., Peterson and King 1975). In the outer regions, the gas will readily dissipate from the cluster. In the central regions, the escape velocity (which varies as $[M(r)/r]^{1/2}$) will be much greater because of the concentration of mass toward the center of globular clusters (King 1962, 1966) and so the gas would be expected to collect in the central regions (Hills and Klein 1973; Knapp, Rose, and Kerr 1973). More detailed calculations, such as those of Scott and Rose (1975), show that most of the emission should be strongly peaked near one core radius, although one may expect that the detailed distribution will depend upon the

[6] In case A, which is valid for a nebula that is optically thin to such photons, the value of $\alpha_{4-2}h\nu = 8.3 \times 10^{-26}$ and the derived upper limits given in this paper should be increased by about 50 percent.

model adopted. Then $N_e \sim$ mass of gas in solar masses $\times$ 1.989 $\times$ $10^{33} m_{\rm H}^{-1} V^{-1}$, i.e.,

$$N_e \sim 77.3M/D_c^3, \tag{A4}$$

where $D_c = 2r_c$. Combining equations (A3) and (A4), we find

$$M \leqslant 2.17 \times 10^{-2} d\theta'(CD_c^3)^{1/2} \text{ solar masses} \tag{A5}$$

under case B conditions. Values for d, θ', C, and D_c are given in Table 1 for each cluster.

h) *The Planetary Nebula in M15*

One observation of M15 presents an exception to the use of equation (A5) for deducing the mass. In all cases except M15, the entrance aperture of the interferometer was centered on the globular clusters by eye; in the case of M15 two observations were made. The 1974 Hα observation was centered on the cluster and included the planetary nebula within the entrance diaphragm, while the 1975 observation excluded it. As shown in Figure 1, we readily detected emission lines at the wavelengths of Hα and [O III] λ5007 when the planetary was in the diaphragm. We thus use equation (A3) to estimate the count rate to be expected from the planetary nebula, namely, $C \geqslant 27.6MN_e/\theta^2 d^2$. Assuming that essentially all the light was in the diaphragm ($\theta' = 2'$), and taking d = 10.0 kpc (Peterson and King 1975), $M = 0.018\ M_\odot$, and $N_e = 1.03 \times 10^4\ \mathrm{cm}^{-3}$ (Peimbert 1973), we find $C \approx 13\ \mathrm{s}^{-1}$. The derived mass for the M15 nebula is quite low; taking a value more like those found for other planetaries, $M \approx 0.1\ M_\odot$ (e.g., Westerlund 1968) would yield $C \approx 71\ \mathrm{s}^{-1}$. The observed count rate at the peak is $\sim 29\ \mathrm{s}^{-1}$ above underlying Hα absorption derived from the second observation. Given the large uncertainties involved, we can reasonably conclude that the emission observed from the central regions of M15 is consistent with the interpretation that it is all associated with the planetary nebula—i.e., that any contribution from interstellar gas in the core of the globular cluster itself is insignificant. Furthermore, it seems unlikely that similar planetary nebulae exist in the central regions of the other 25 globular clusters that we have observed.

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Note added in proof.—The paper by Bahcall and Ostriker (1975) does not state what value was taken for the central R_{pc} of the cluster in giving the formula for Hβ flux; in applying their formula, we have implicitly assumed that the emitting region was fully covered by the interferometer diaphragm. Dr. Bahcall has recently written to us: "For a core radius $\sim$0.4 pc . . . we expect $\sim$0.1 $M_{\odot}$. . . . The second estimate of Hβ given three paragraphs from the end of our paper seems . . . overoptimistic by a factor of 10^2 (the expected flux at Hβ should be $\sim 10^{-15}$ ergs cm^{-2} $d_{10}{}^{-2}$ kpc if the gas is distributed uniformly over a core radius)." The numbers given in the third column of our Table 3 should therefore be divided by $\sim 10^2$.

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