OBSERVATIONAL SEARCHES FOR DARK HALOS

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ABSTRACT. A review of observational searches reveals the following constraints for the constituents of dark halos: (1) Optical searches show that these halos are not for a large fraction of their mass made up of dwarfs of spectral type M5 or earlier. (2) K-band (2.2 μ) searches virtually rule out all H- burning Main Sequence stars. (3) IRAS upper limits are consistent with black dwarfs of any age or Jupiters. (4) The inferred metallicity and M/L variations in the spheroid of NGC 7814 are consistent with the hypothesis that the dark matter consists of low mass objects that formed along with the luminous population II.

1. WHERE DO WE LOOK AND FOR HOW MUCH?

This review of observational searches for dark halos will be devoted entirely to spiral galaxies. Current best estimates show that within the cut-off radius R_{max} of the disk only about one-third of the total mass within this radius as indicated by the rotation curve is contained within the disk itself. There are three general methods to estimate the disk mass: (i) The disk surface density can be estimated at various radii by comparing the vertical velocity dispersions (generally measured in nearly face-on spirals) to the vertical scaleheights (measured in edge-on galaxies). The components usuable for this are the HI-gas, which has a constant velocity dispersion of 7-10 km s^{-1} but increasing thickness with radius, and the old disk populations, which have a constant exponential scaleheight of 0.35±0.1 kpc but its vertical velocity dispersion decreasing with radius (see e.g. van der Kruit and Shostak, 1984; van der Kruit, 1981; van der Kruit and Searle, 1982; van der Kruit and Freeman, 1985). (ii) The rotation curve may contain a "truncation" feature at the cut-off radius, whose amplitude is a measure of the disk to halo mass-ratio (Casertano, 1983). (iii) Rotation curves can be analysed in terms of an exponental disk determined from surface photometry and a specified halo density distribution (Bahcall, 1983; Carignan and Freeman, 1985; van Albada et al., 1985). This gives a somewhat wide range of mass-ratios for the extreme possibilities of "maximum" and "minimum" disk (see also Sancisi and van Albada in this volume).

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The first method appears to be the most restrictive and widely applicable in practice and currently suggests within R_{max} that M(halo)/M(disk) = 1.5 - 3. Also over a limited range in R it is consistent with a constant old disk M/L with radius with a value of 6 ±2 $M_\odot/L_{\odot,B}$ for H = 75 km s^{-1} Mpc^{-1}. The three methods indicate that a halo of dark matter must exist that is significantly less flattened than the disk. In what follows I assume it to be spherical (see also Rubin in this volume) and to have roughly a density distribution $\rho \propto R^{-2}$. On the sky this implies a surface density distribution $\sigma \propto R^{-1}$.

2. OPTICAL AND NEAR-INFRARED SEARCHES

The most important searches reported in the literature are listed in Table 1. A number of remarks can be made:

- The first study by Freeman et al. (1975) on NGC 253 already showed that any dark matter must have an $(M/L)_B$ in excess of several hundred. This photographic study therefore already indicated that dark halos cannot be made up for a considerable fraction of their mass of main sequence stars earlier than spectral type about M5.

Table 1 - Searches for dark halo's

Authors	Year	Galaxies	Type	Bands
Freeman et al.	1975	N253	Sc	B
Frankston & Schild	1976	N4565	Sb	VI
Gallagher & Hudson	1976	I2233	Sd?	BVi
Hegyi & Gerber	1977	N4564	Sb	VI
Kormendy & Bruzual	1978	N4565	Sb	V
Spinrad et al.	1978	N4565, 4594, 253	Sb, Sb, Sc	Br
Hegyi & Gerber	1979	N4565	Sb	RI
Davis et al.	1980	N4565	Sb	B
Hohlfeld & Krumm	1981	N2768, 4762, 4203, 4565	So, So So, Sb	JK
Boughn et al.	1981	N4565	Sb	K
Jensen & Thuan	1982	N4565	Sb	BVrI
Skrutskie et al.	1985	N2683, 4244, 5907	Sc	VK

- Later studies in the optical bands (B, V, r, etc.) using different and often very clever and innovative techniques have not been able to significantly improve on this. This is mainly a result of the very sharp rise at optical wavelengths in M/L for dwarfs later than M5. For example we may look at Van Biesbroeck 10 which is believed to be very close to the minimum mass necessary for H-burning (Greenstein et al., 1970):

M5	0.22 $M_\odot$	400 $M_\odot/L_{\odot,B}$	60 $M_\odot/L_{\odot,V}$	9.6 $M_\odot/L_{\odot,K}$
VB10	0.09	1.7×10^5	3.8×10^4	35

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- These numbers also show that one can profitably observe at near-IR wavelengths such as K-band (2.2 μ). There the limits are a few tens $M_\odot/L_\odot$, which essentially rules out all H-burning Main Sequence stars as a major constituent.
- Almost everybody's favorite appears to be NGC 4565. Kormendy (1982) has produced from all the data an accurate minor axis profile which extends to about 6.5 arcmin where the surface brightness is reported as ~31 B-mag arcsec^{-2} (see Fig. 1). Two remarks can be made: (i) Beyond the "kink" at about 50 arcsec the profile has $I \propto r^{-2.55}$ which is very much steeper than expected from a dark halo with constant M/L. (ii) Such a halo with $(M/L)_B$ = 75 (which fits the observed surface brightness at ~50 arcsec) still would have a surface brightness of about 27 B-mag arcsec^{-2} at 7'. Now this is the distance at which observers usually have assumed to observe pure sky!

This last point is worth investigating somewhat further. Most authors have been aware of this and have made remarks to this extent in their papers. E.g. Hegyi and Gerber (1977) "have briefly taken obser-

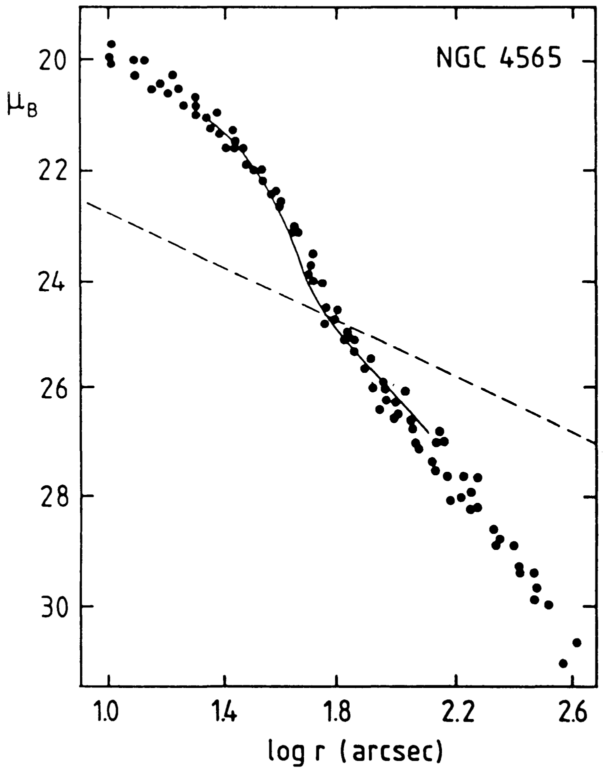

Fig. 1 - The minor axis profile of NGC 4565 as compiled by Kormendy (1982). The dashed line indicates a $\sigma \propto R^{-1}$ halo as expected from the rotation curve with M/L ≈ 75 (and assumed spherical). Beyond 50 arcsec the observations show $I \propto R^{-2.55}$.

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vations" at somewhat larger distances and Davis et al. (1980) note an absence of a slope in their data between 5 and 8 arcmin. However, a detailed comparison shows that their limits are only marginally inconsistent with the variations expected from an $I \propto R^{-1}$ halo with $(M/L)_B \approx 75$. The point here is of course that in such a halo the surface brightness will become fainter by only 1 mag when the distance from the centre is increased by a factor 2.5. The non-existence of such halos is certainly not as secure as a cursory glance at the literature would suggest. On the other hand it may be too severe to suspect Kormendy's profile as very wrong, since a serously wrong sky level would result in a strong decline at 5-6 arcmin, which is not observed.

3. LIMITS IN NGC 5907

Obviously the analysis of surface brightness distributions is seriously complicated by the presence of a spheroid, and there are clear advantages in chosing an essentially bulge-less, edge-on system. Now except for the last entry in Table 1 only Galagher and Hudson (1976) have chosen such a system; however IC 2233 is a dwarf galaxy. The most favorable choice is NGC 5907 for which there exists both surface photometry and mass models. As the picture in the Hubble Atlas shows, it has at most a very tiny bulge. I will proceed to derive the formal upper limits and will also use data at much larger radii than in NGC 4565 to determine the sky level.

I use a distance of 11 Mpc (H = 75 kms^{-1} Mpc^{-1}), so that the galaxy has a disk cut-off at 19 kpc (6 arcmin). Estimates for the disk mass have been given as 8×10^{10} $M_\odot$ by van der Kruit and Searle (1982; corrected to an $(M/L)_{old\ disk} = 6\ M_\odot/L_{\odot,B}$) and 9×10^{10} $M_\odot$ by Casertano (1983). This leads to halo masses within 19 kpc of 14×10^{10} $M_\odot$ and 13.5×10^{10} $M_\odot$ respectively. If spherical the dark halo has ρ ($M_\odot$ pc^{-3}) $\approx 5.9 \times 10^{-1}$ R^{-2} (kpc) and surface density σ ($M_\odot$ pc^{-2}) $\approx 1.8 \times 10^3$ R^{-1} (kpc) if extending to infinity.

For the optical surface photometry I use the data from van der Kruit and Searle (1982) in the J and F bands. The plates therein were digitized over an area of 17 × 34 arcmin ($\alpha \times \delta$) and have been analysed in 4-arcsec square pixels. A new sky fit was performed to a linear polynomial (sloping plane) using only pixels more than 14 arcmin from the centre of NGC 5907. Over area's of the plate values for the extended surface brightness were determined from an analysis of histograms of the pixel values. The bright pixels with stars where ignored and a Gaussian centered on the median pixel value was fitted to the peak. The widths of these correspond to r.m.s. values of ~1.2% of sky surface brightness.

The resulting medians in rings on the sky are shown in Fig. 2. To obtain these for R < 6' only pixels with distance z > 2' from the plane of NGC 5907 were taken. It is clear that for z > 3' there is no halo in excess of 0.2% of sky, which corresponds to surface brightnesses of 28.8 mag arcsec^{-2} in J and 28.0 in F. Since the difference of 0.8 mag is

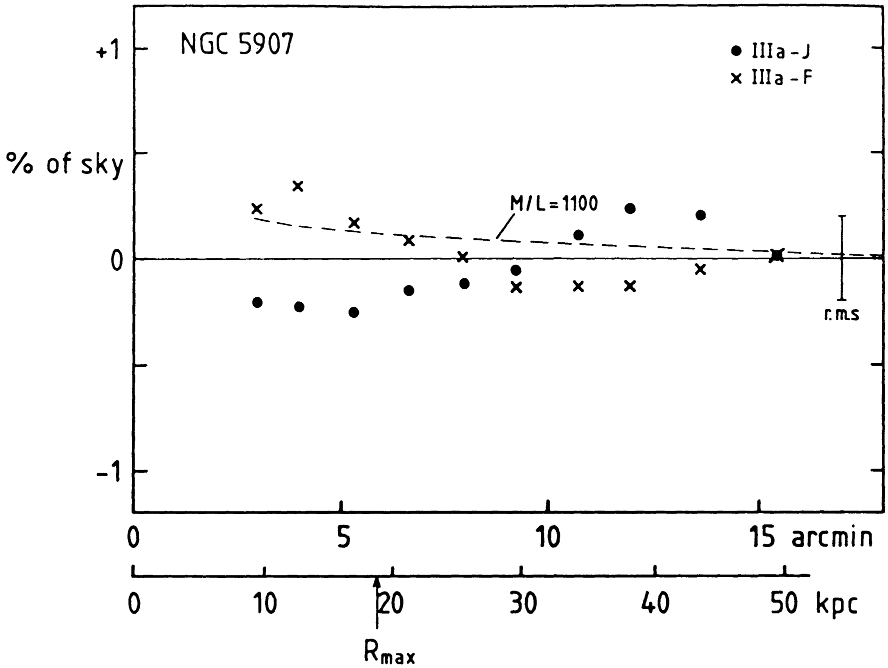

Fig. 2 - Median pixel values, expressed in percent of sky surface brightness in rings centered on NGC5907. The dashed line shows an $I \propto R^{-1}$ halo with M/L = 1100.

equal to the sun's colour index in these bands I find the same M/L-values in both colours.

We may integrate the data over the area R < 6', z > 2' to find that $L < 1.2 \times 10^8 L_\odot$ or M/L > 760. Also we may take an upper limit at R = 3' as above to find M/L > 1100. For comparison:

M5-dwarf	$(M/L)_J = 280\ M_\odot/L_{\odot,J}$	$(M/L)_F = 80\ M_\odot/L_{\odot,F}$
VB10	1.2×10^5	1.8×10^4

Next we take the K-band upper limits from Skrutskie et al. (1985) along the minor axis. These lead to the following results:

z = 1.0 arcmin (3.2 kpc)	$M/L > 36\ M_\odot/L_{\odot,K}$
z = 1.5 arcmin (4.8 kpc)	$M/L > 20\ M_\odot/L_{\odot,K}$

Again for comparison

M5-dwarf	$M/L = 10\ M_\odot/L_{\odot,K}$
VB10	$M/L = 36\ M_\odot/L_{\odot,K}$

The values derived here are based on a definite mass model that incorporates a measured disk mass independent of the general shape of the rotation curve. Also the optical data utilise a sky-fit at more than 2 disk radii (the K-band data are obtained wilth a wobbling secondary with a throw of 8 arcmin; an $I \propto R^{-1}$ halo would have a surface brightness at the sky position 6-8 times fainter than at z = 1-1.5 arcmin). We probably have here the best defined upper limits. They show that dark halos cannot be made up of H-burning Main Sequence stars, at least not for a considerable fraction of their mass. It would be profitable to push the limits in the K-band further by a factor two or so.

4. IRAS MEASUREMENTS

Deep maps of a number of edge-on galaxies (NGC 4565, 4244, 891, 5907, etc.) have been obtained with IRAS and put at my disposal (T. de Jong and R. Wainscoat, private communication). None of these show evidence for emission at large distances from the plane. I give below again detailed numbers for NGC 5907. For some of the data see Fig. 3.

For definiteness I compare the data with dark halos made up of the following objects:
- Main Sequence dwarfs of mass ~0.09 $M_\odot$ (such as VB10)
- Black dwarfs. Here I use Tarter's (1975) cooling curves as adapted by Staller and de Jong (1981):

$$L/L_\odot = 8.57\ (M/M_\odot)^{1.91}\ (t/yr)^{-0.836}$$

$$R/R_\odot = 0.23\ (M/M_\odot)^{-0.22}\ (T_e/K)^{-0.096}$$

- "Jupiters". I take the relevant values for the planet, keeping in mind that it radiates more energy than it receives from the sun.

Some relevant parameters are summarized in Table 2. The black dwarfs are assumed to be either primordial (t = 15 Gyr) or young (t = 1 Gyr). The radiation is assumed purely black body and λ_m is the wavelength of the maximum in the Planck curve.

Table 2 - Parameters of dark objects

Object	age(Gyr)	$M(M_\odot)$	$L(L_\odot)$	$R(R_\odot)$	$T_e(K)$	$\lambda_m(\mu)$
RD		9×10^{-2}	9.7×10^{-4}	0.023	2600	1.1
BD	15	7×10^{-2}	1.7×10^{-5}	0.28	700	4.1
BD	1	7×10^{-2}	1.6×10^{-4}	0.26	1270	2.3
BD	15	1×10^{-2}	4.0×10^{-7}	0.48	210	13.6
BD	1	1×10^{-3}	3.9×10^{-6}	0.45	380	7.5
BD	15	1×10^{-3}	4.9×10^{-9}	0.91	51	56
JUP		9.5×10^{-9}	1.0×10^{-9}	0.10	100	28

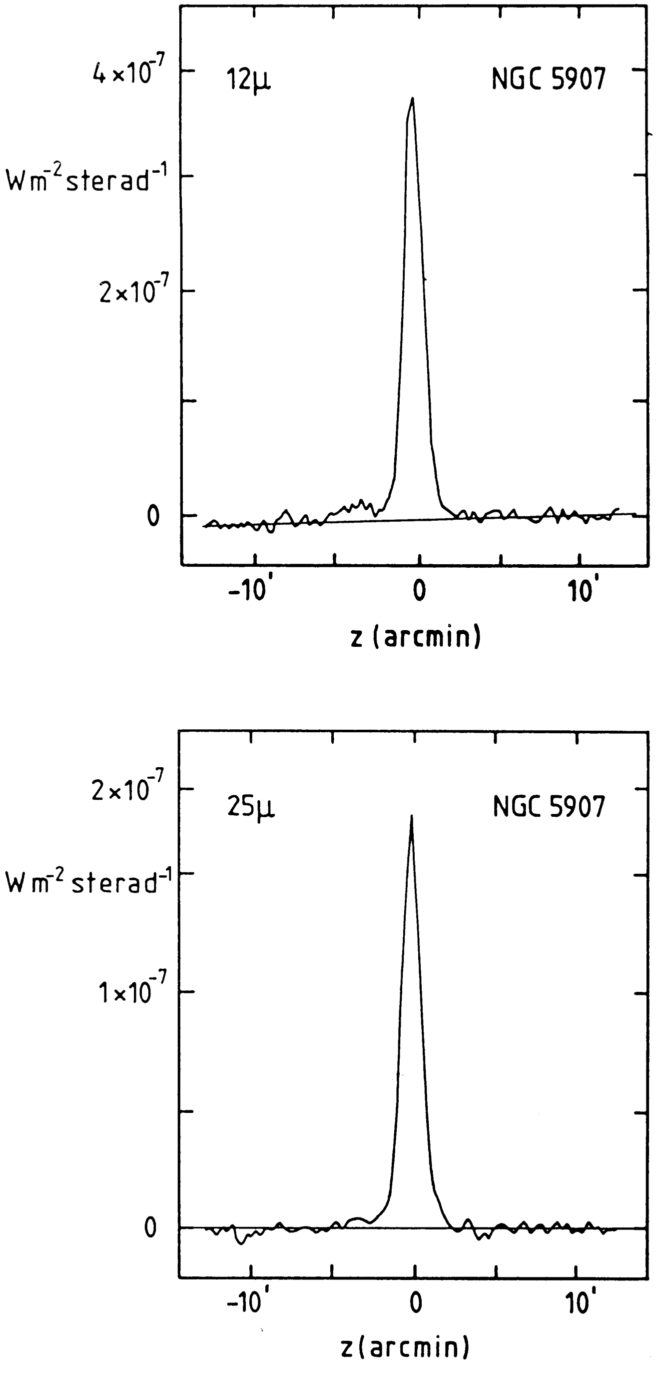

Fig. 3 - Minor axis scans obtained by IRAS of NGC 5907 at 12 and 25 micron. No significant emission is detected at $|z| \gtrsim 2$ arcmin.

The predicted fluxes and the upper limits are compared in Table 3. The IRAS results are consistent with the halo being made up of any of the objects used in the comparison, i.e. all kinds of collapsed objects less massive than Main Sequence stars.

Table 3 - Comparison of IRAS data on NGC 5907 with predictions of halos made up of the various objects given in Table 2.

λ z	12 μ 2' (6.4 kpc)	25 μ 2' (6.4 kpc)	60 μ 4' (12.8 kpc)	100 μ 5' (16.0 kpc)
$\log_2$ f(IRAS) Wm^{-2} $sterad^{-1}$	$\lesssim -8.3$	$\lesssim -8.7$	$\lesssim -8.7$	$\lesssim -8.7$
Object (t,M)				
RD	-10.9	-11.8	-13.1	-15.1
BD (15,0.07)	- 9.4	-10.3	-11.4	-13.4
BD (1,0.07)	- 9.1	-10.0	-11.2	-13.2
BD (15,0.01)	-10.0	-10.0	-10.8	-12.7
BD (1,0.01)	- 8.9	- 9.4	-10.5	-12.4
BD $(15,10^{-3})$	-12.9	-11.6	-11.8	-13.6
JUP	-16.1	-12.2	-11.0	-12.4

5. EVIDENCE FROM COLOUR GRADIENTS IN SPHEROIDS

There are two ways in which colour gradients in spheroids can tell us anything about the constituents of dark halos. In the first place, a change of the make-up of the spheroids towards very low-mass stars would reveal itself by a gradual reddening with radius. Close scrutiny in this respect has again been performed in the spheroid of NGC 4565. No clear, significant change has been reported (Hegyi and Gerber, 1979; Boughn et al., 1982; Thuan and Jensen,1982).

A second way in which the dark halo may manifest itself is by a radial gradient towards lower metal abundance which would give rise to a increasingly bluer colour with radius. This would result when an increasing amount of low mass objects have been formed along with the luminous population II at larger galactocentric distance, while the initial mass function of the metal producing stars is invariant. This is so because these low mass objects act as sinks for the products of nucleosynthesis, leaving the stellar population with a lower mean abundance when the fragment of the protogalaxy has evolved to completion (see e.g. van der Kruit and Searle, 1982b). Simple models indicate that this mean metallicity should be proportional to the "yield" of heavy elements and therefore to the local M/L.

Such colour changes are often seen in the spheroids of spiral galaxies (Wirth, 1981; Wirth & Shaw, 1983; van der Kruit and Searle, 1981; 1982b), and are generally believed to be due to a change in metallicity (see also Mould, 1984). In this respect the Sab galaxy NGC 7814 offers a unique possibility, because it not only displays a sizable colour gradient, but also has an insignificantly small disk (Van der Kruit and Searle, 1982b). Its flat HI rotation curve can uniquely be interpreted in terms of a spheroid mass distribution. The $R^{1/4}$ surface brightness distribution and the R^{-2} density distribution indicate an increase in M/L by a factor 10 between 3 and 21 kpc (major axis distance). At the same time the colour changes of $\Delta(U-B) = 0.3\pm0.3$ mag. and $\Delta(B-V) = 0.7\pm 0.3$ mag span the total range of colour index variation among Galactic globular clusters. This also implies a change in metallicity of an order of magnitude, in agreement with the predictions.

Other interpretations may certainly be invoked; nevertheless, the spheroid of NGC 7814 displays the signs expected if the dark matter consists of low mass objects formed along with the luminous constituents of population II.

As a final point I note the interesting fact that the two edge-on galaxies NGC 891 and 7814 have identical rotation curves which are flat between about 3 and 20 kpc at 220 km s^{-1}. Yet NGC 891 is strongly disk-dominated and NGC 7814 spheroid-dominated in their light distributions. Constant M/L ratio's of the luminous components would give rise to grossly different rotation curves (see Fig. 1 in Van der Kruit, 1983).

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DISCUSSION

ROBERTS: In NGC 5907 you have a value of M/L in the K band of > 36, and you gave a value of M/L = 36 in the K band for van Biesbroeck's star. Is this the basis for your eliminating all main sequence stars?

VAN DER KRUIT: Yes. You find similar limits in other galaxies, notably NGC 4565, in the literature. The limits also depend on the fraction of the mass in the disk, and on whether the halo is spherical. The conclusion is not very strong. But the observations rule out main sequence stars unless you make models that are very contrived.

TYSON: On faint photographic surface photometry: Photographic plates have served astronomy well, but it is dangerous to attempt surface photometry at 30 mag arcsec^{-2} due to systematic errors over large spatial wavelengths. Whereas the sky noise decreases like the number of pixels and plates averaged, systematic noise does not decrease like $1/\sqrt{N}$.

BURSTEIN: The reflection nebulae which create the "galactic cirrus" place a fundamental limit on the uniformity of the sky background, as pointed out 10 years ago by Sandage and more recently by de Vaucouleurs. A reddening of $E(B-V) \approx 0.02 - 0.04$ mag corresponds to reflection nebulae of $\sim 27 - 28$ mag arcsec^{-2}. Since much (but not all!) of the sky has reddenings of at least this value, and since IRAS measures have emphasized the intrinsic patchiness of the cirrus, these reflection nebulae will place an upper limit on the uniformity of the sky background at all optical wavelengths.

VAN DER KRUIT: Indeed these reflection nebulae are a fundamental limitation. However, NGC 5907 seems to sit in a relatively uniform area of the sky, so I was able to derive an upper limit that is rather faint. I think that one should worry seriously about galactic cirrus if ever a positive detection of a halo is reported.