Gaseous Halos and the Interstellar Disk-halo Connection in Spiral Galaxies

Ralf-Jürgen Dettmar

(*Astronomical Institute, Ruhr-University Bochum, Germany*)
dettmar@astro.ruhr-uni-bochum.de

Abstract The presence of gaseous halos in star forming disk galaxies is reviewed in the context of a proposed disk-halo connection of the interstellar medium (ISM). New results from a quantitative survey for H^+ halos of edge-on galaxies (Rossa & Dettmar 2002) are presented. The data confirm that the presence of diffuse ionized gas (DIG) in the disk-halo interface of spiral galaxies is related to star formation processes in the underlying disk and allow us to establish a minimum energy release per unit area that is required to start the disk-halo mass exchange. By comparing some recent observational results for diagnostic emission lines with model predictions from photoionization we demonstrate that the origin and excitation of the DIG is, however, still not completely understood and that a discussion gives important constraints for models of the ISM. In comparison with similar findings for the Milky Way the need for an additional heating source is established. Special emphasis is given to some recent developments. In particular, new kinematical information for the DIG layer in NGC 5775 from ESO/VLT long-slit spectra is discussed in connection with the magnetic field structure in the halo of this object as deduced from VLA radio-continuum polarization data (Tüllmann et al. 2001). Finally, the rôle of dust for the physical processes in the disk-halo interface is briefly addressed.

Key words galaxies: evolution—galaxies: ISM—galaxies: halos—ISM: general

1 Introduction

Ever since the first evidence for radio-continuum halos in the Milky Way and other galaxies – such as in the prototypical case of NGC 4631 – the physical processes for the origin of gaseous galactic halos were mainly sought in the feedback of energy into the interstellar medium (ISM) by young stars through winds, the interstellar radiation field, and (multiple) supernova explosions. From this general idea the concept of the disk-halo interaction emerged in which the disk medium can connect to the halo. This is described in different model approaches in terms of galactic fountains, chimneys, or super-bubble-outbreak by theory. Models for the gas transport from the disk into the halo are proposed in several theoretical approaches such as the chimney scenario (Norman & Ikeuchi 1989), galactic fountains or superbubble blow-outs (e.g., McLow & Ferrara 1999).

Observational support for the idea of such a large scale matter exchange between disk and halo comes from observations of gaseous halos in external galaxies (e.g., Dahlem 1997, Dettmar 1998). While several phases of the ISM – from cold HI to X-ray coronae and even molecular gas – have meanwhile been found in the halos of spiral galaxies, the H^+ with a scale height of typically 1 kpc in the disk-halo interface of spiral galaxies (corresponding to the Reynolds layer in our Milky Way) represents a particularly important constituent, since it is relatively easily observed in the optical (Dettmar 1992, 1998). Therefore, imaging in and spectroscopy of optical emission lines allow us to study the distribution and excitation of this Diffuse Ionized Gas (DIG, or WIM for Warm Ionized Medium) with a spatial resolution not achievable for other phases of the ISM in external galaxies. To demonstrate the distribution of DIG in halos of galaxies we reproduce in Fig. 1 a Hα-image of one of our target galaxies (Rossa & Dettmar 2000).

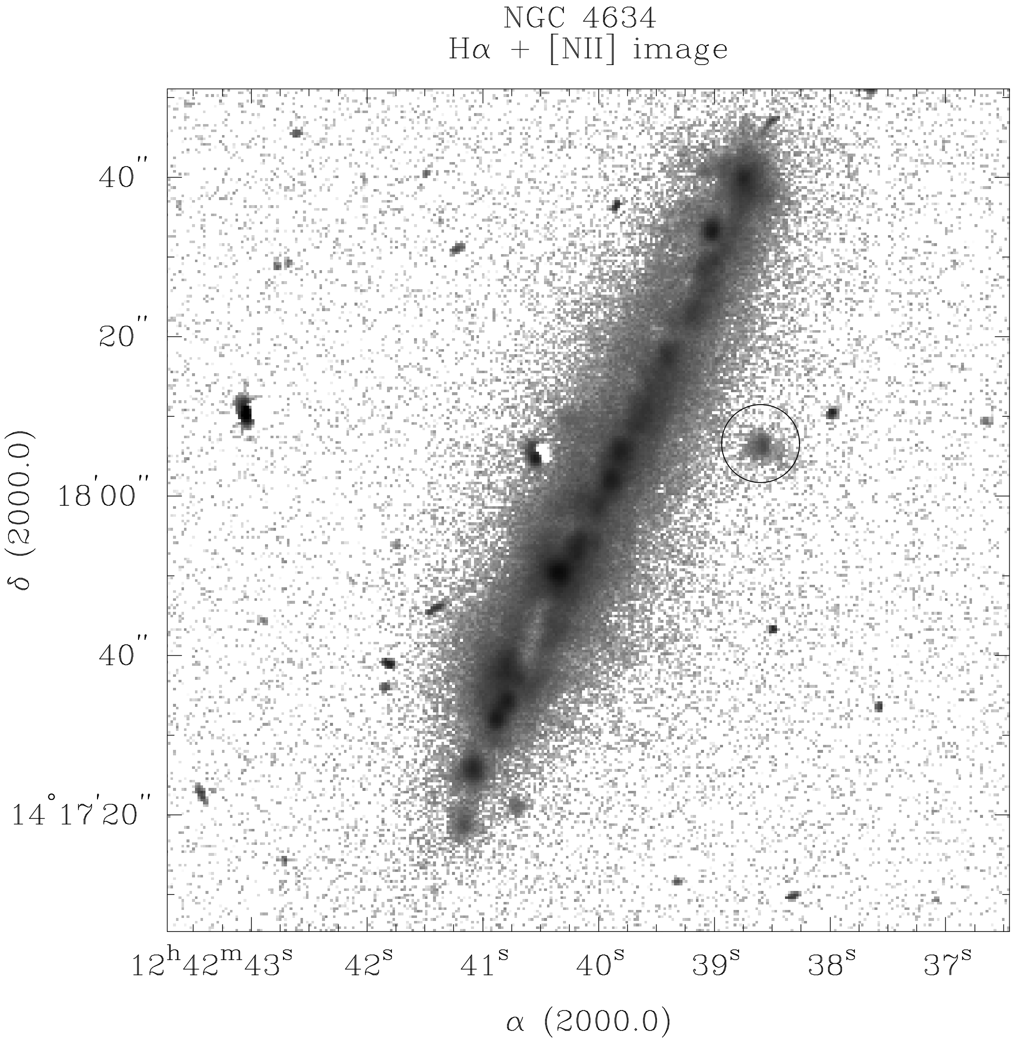

Fig. 1 The galaxy NGC 4634 exhibits a bright and thick layer of extraplanar H^+ (from Rossa & Dettmar 2000). The encircled object is a probable dwarf companion

In the following we present results of an ongoing investigation of extraplanar DIG (eDIG) in edge-on galaxies. Based on a quantitative Hα survey and emission line spectroscopy we are trying to answer questions such as: How common are galactic gaseous halos? What is the minimal SFR per unit area which triggers gaseous galactic outflows? Is there a correlation between gaseous halos and other halo components such as radio continuum "thick disks" that are seen in several edge–on galaxies? Is the magnetic field structure in galaxies related to outflows? What are the ionization and excitation processes for DIG at high galactic latitudes?

2 DIG Halo Gas and the Star Formation Rate

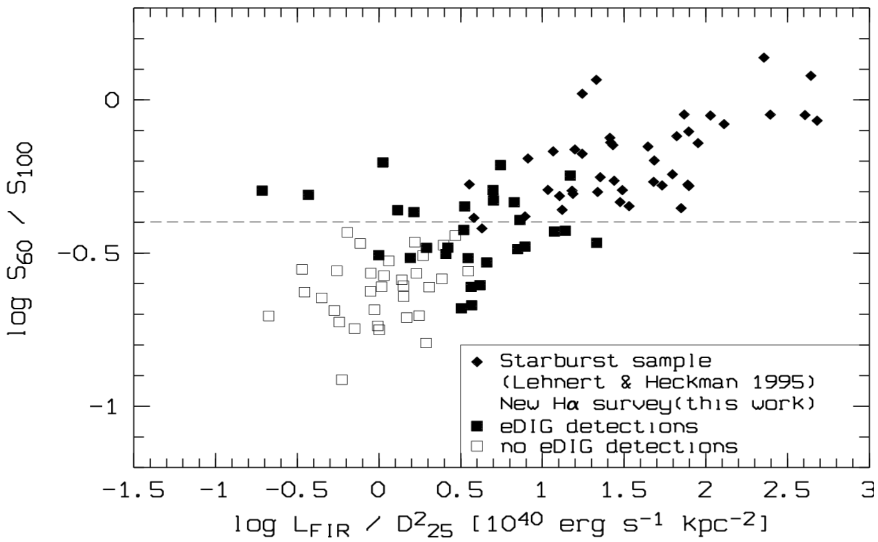

Fig. 2 Diagnostic DIG diagram for starburst and non–starburst edge–on galaxies. The ratio of the FIR fluxes at 60μm and 100μm (S_{60}/S_{100}) is plotted versus the ratio of the FIR luminosity to the optical galaxy diameter squared of the 25^{th} mag in units of 10^{40} erg s^{-1} kpc^{-2}. The filled lozenges denote the starburst galaxy sample studied by Lehnert & Heckman (1995). Squares indicate our new observations with filled symbols for detections of H^+ gas in the halo and open squares for non-detections (from Rossa & Dettmar 2003).

A halo component of DIG for external galaxies was first discovered in NGC 891 a decade ago (Dettmar 1990, Rand et al. 1990). A few small samples have been studied so far (e.g., Pildis et al. 1994, Rand 1996; Rossa & Dettmar 2000), however, more complete and larger samples are required to clearly demonstrate the suggested correlations of halo gas properties with the star formation rate (SFR) in the disk. In particular, a broader range in SFR has to be covered since up to now emphasis was given to starburst galaxies. An attempt to relate the presence of DIG in halos of spiral galaxies to their far infrared (FIR) properties as a measure of the SFR is shown in Fig. 2. Here a sample of galaxies was chosen such that it supplements the previously studied "starburst" objects at the low activity end. If the starformation rate per unit area is low as determined by the FIR luminosity normalized to the disk surface the presence of halo DIG indeed diminishes. The FIR luminosity per unit area therefore seems to be a promising indicator for the presence of halo H^+ gas and a minimum SFR per area seems to be required to drive the disk-halo interaction (Rossa & Dettmar 2002).

3 Ionization of Halo DIG

It has been shown in the past (Domgörgen & Mathis 1994, Golla et al. 1996, Tüllmann & Dettmar 2000) that the emission line characteristics of DIG in galactic halos is not explained by photoionization in a straight forward manner. The detailed ionization structure rather remains a major problem for pure photoionization models and several recent studies

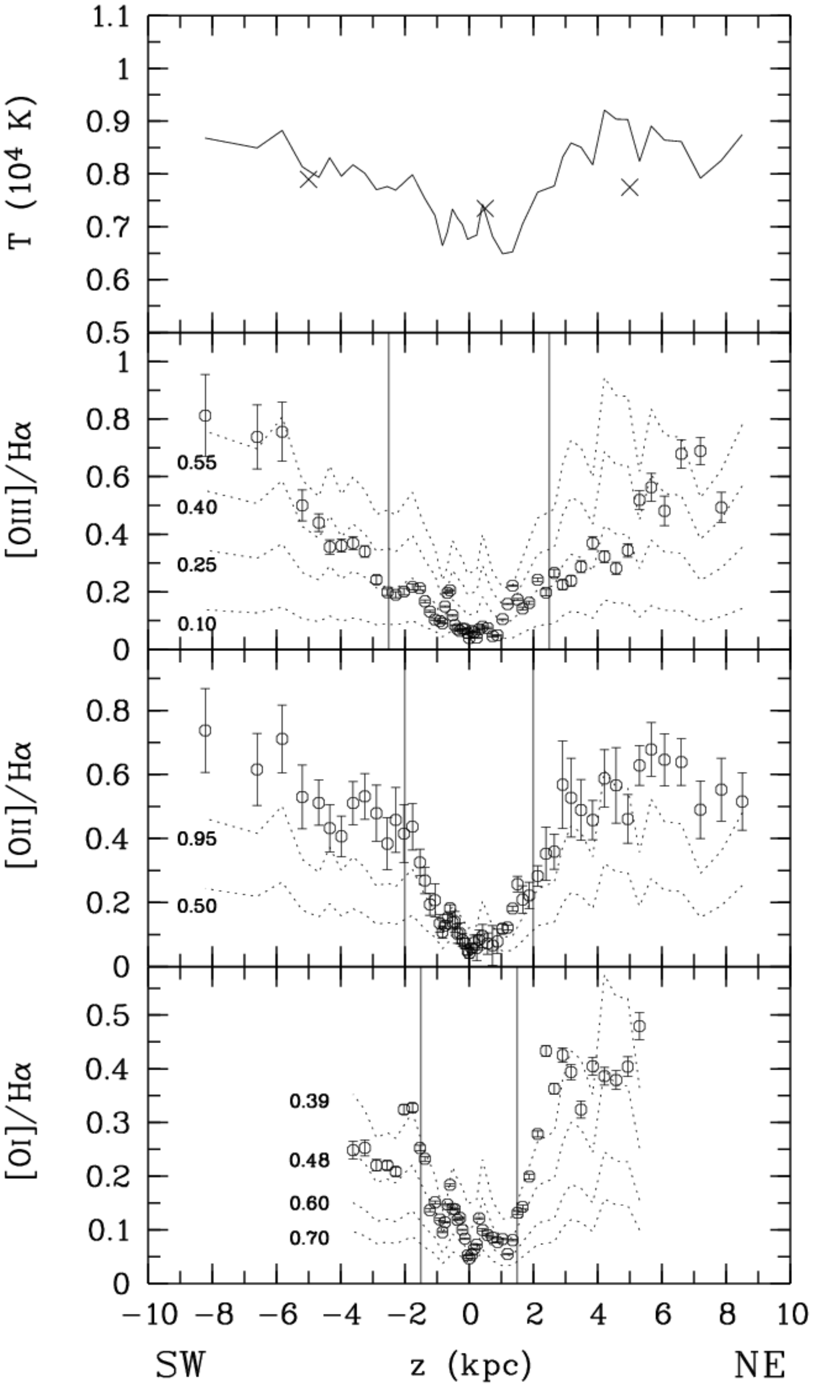

Fig. 3 Emission line rations and temperature profile (uppermost panel) of the DIG in NGC 5775 along a slit cutting the SE disk perpendicular at ∼4 kpc from the nucleus (from Tüllmann et al. 2001).

for extraplanar DIG in the Milky Way and NGC 891 (Reynolds et al. 1999, Rand 1997, 1998) therefore claimed a need for secondary heating and/or ionizing sources. Ideas for such supplemental mechanisms include shock ionization, turbulent dissipation, and magnetic reconnection. In order to examine possible ionization and/or excitation mechanisms of the eDIG we compared spectroscopically observed emission line ratios and diagnostic diagrams with model predictions (photoionization codes of Mathis 1986 and Domgörgen & Mathis 1994) for a small sample of edge-on galaxies (Tüllmann & Dettmar 2000). The relation between the [SII]/Hα and [NII]/Hα ratios which are both raising with increasing distance from the galactic mid-plane is also observed in the Milky Way. Here it is explained as an effect of an increase of temperature at higher latitudes (Reynolds et al. 1999). This behavior of emission lines for halo DIG is also observed in NGC 5775 as shown in Fig. 3. The very deep spectrum of this galaxy, tracing diagnostic emission lines out to 10 kpc from the mid-plane, was observed with the FORS1 instrument at the ESO VLT-UT1. From the observed emission line ratios the temperature profile in the upper panel of the figure was deduced showing the same general behaviour of an increasing temperature as it is discussed for the Milky Way (see above).

4 Kinematics of Halo Gas

A particularly striking result is related to the kinematical information regarding the DIG layer which is extracted from the same deep VLT spectrum discussed in the previous section. As shown in Fig. 4 the velocity of the DIG at a galactocentric distance of $\approx$4 kpc is dropping from the rotational velocity in the disk plane to systemic at a distance of $\sim$10 kpc above the plane. This is most likely not just a local perturbance in the velocity field since similar spectra of NGC 5775 by Rand (2000) show the same phenomenon for two different slit positions. A model to explain such a velocity field reaching systemic velocity at large distances is currently not available. Observations of UV absorption line systems by Côtè et al. (2000), however, show a similar phenomenon and therefore ask for a more general solution. Theoretical attempts may require a reconsideration of all relevant processes such as the discussion of forces by magnetic tension as introduced by, e.g., Benjamin (2000) in response to the observed slight drop in rotational velocity for halo gas in NGC 891 by Rand (1998) and Swaters et al. (1997).

5 The Magnetic Field Structure in the Halo

The presence of a disk-halo interaction in a galaxy traced by DIG in the halo is also supported by the frequently found simultaneous presence of other ISM constituents such as X-ray emitting plasmas or cosmic ray electrons observed in the radio continuum. The break-out condition for cosmic rays as a function of star formation rate per unit area is discussed by Dahlem et al. (1995) and a compilation of observations of edge-on galaxies in Hα, radio continuum, and X-rays is given in Dettmar (1998).

The previously discussed case of NGC 5775 also shows a prominent radio continuum halo (as well as a X-ray halo and extraplanar CO emission; Lee et al. 2001) and a study of its polarization characteristics with the VLA reveals even an highly structured large scale magnetic field with field lines opening up into the halo (Fig. 5). It is well possible that the velocity structure of the halo gas described above in Sect. 4 is related to the origin of the magnetic field since the theory of galactic dynamos relates the z-component of the magnetic field and a shear caused by the gradient dv/dz to the generation of an azimuthal magnetic component. This is, e.g., discussed by Men and Han (2003) in these proceedings.

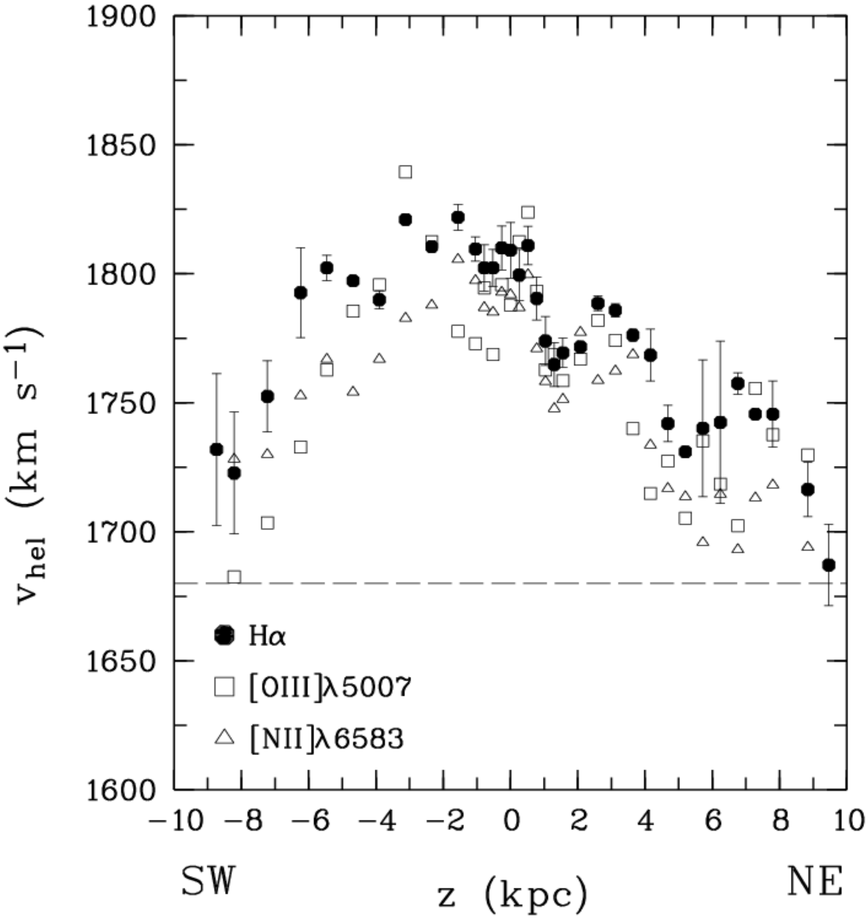

Fig. 4 DIG kinematics along slit perpendicular to major axis. The velocity drops from rotational velocity at the midplane to systemic in the halo (from Rossa & Dettmar et al. 2003).

6 Dust in the Halo

Since the star formation process in the disks will also locally enhance the radiation field it was suggested more than a decade ago that dust could be elevated by radiation pressure from the disk into the halo (Franco et al. 1991). Ferrara (1997) modeled the evolution in time of the dust distribution under the influence of the radiation field caused by an OB association and showed that the dust would be dispersed into a large volume. This, however, is in contrast to the observed dust distribution in several galaxies. Sofue et al. (1994) demonstrate that the dust in the disk of NGC 253 is highly structured in large scale arches much resembling solar prominences in shape. Also the dust distribution in the edge-on galaxy NGC 891 studied, e.g., by Howk and Savage (1997) is organized in long filaments reaching from the disk into the halo. These filaments end in a level of dust sheets high above the disk plane. The case of NGC 891 is also studied by Rossa et al. (2002) with the high resolution imaging capability of HST and in Fig. 6 we present a first image of the dust distribution from these WFPC observations. The possible influence of magnetic fields

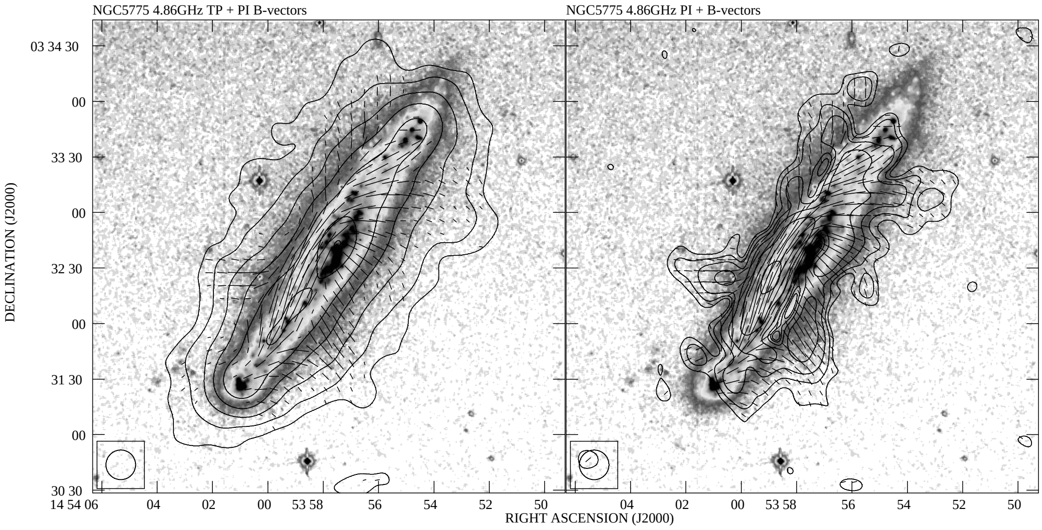

Fig. 5 VLA radiocontinuum map of NGC 5775 at 6cm; the left panel gives total power while the right panel represents polarized intensity. The bars represent the magnetic field direction. For details see Tüllmann et al. (2000).

on the charged dust particles as an additional process to structure the dust distribution in galactic halos was put forward by Shchekinov et al. (1999). In the presence of large scale organized magnetic fields in galactic halos as demonstrated above for the case of NGC 5775 such processes have to be discussed in more detail in the future. It should be mentioned here that in such an environment also the dipole radiation of spinning dust (Ferrara & Dettmar 1994, Draine & Lazarian 1999) could contribute to the radioemission from galaxies at GHz frequencies.

7 Summary

Gaseous DIG halos are found in galaxies with sufficient SFR per unit area. Typically these layers of extraplanar DIG can be traced out to distances of z $\leq$1–2 kpc – sometimes even up to 5 kpc or more – from the mid-plane of the disk. The emission line ratios indicate an increase in the electron temperature of the DIG with increasing hight above the midplane. This behaviour is similar to the Reynolds layer in the Milky Way and a heating mechanism in addition to photoionization is currently being discussed. These H^+ halos seem to be associated with halos of cosmic rays and X-ray plasma as expected if caused by the disk-halo interaction of the ISM. The polarized radiocontinuum emissions indicates an ordered magnetic field in the halo. The peculiar velocity structure of the halo gas in the case of NGC 5775 is possibly related to this ordered magnetic field and also the highly structure dust distribution in the halos of some galaxies could be influenced by magnetic fields due the coupling of charged dust to both the radiation and magnetic fields.

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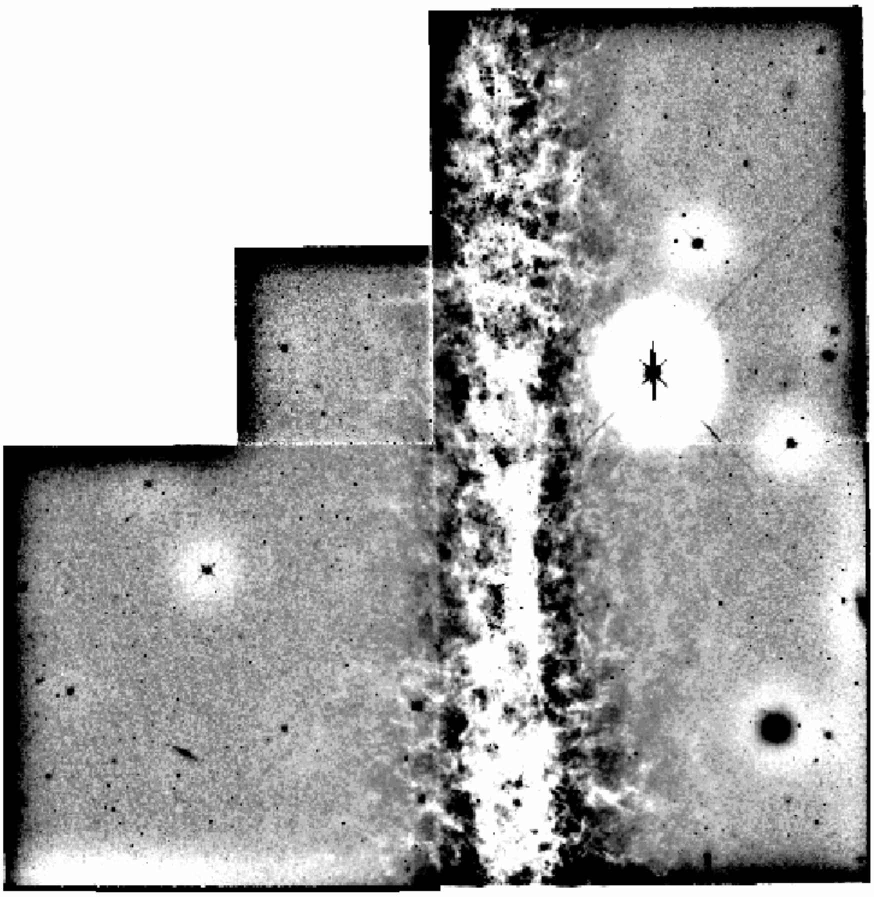

Fig. 6 Unsharp masked R-band continuum image of NGC 891 showing the highly structured dust distribution in the halo. (from Rossa et al. 2002).

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