Discovery of a Giant Stellar Tidal Stream Around the Disk Galaxy NGC 4013

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ABSTRACT

We report the discovery of a giant, low surface-brightness loop-like stellar structure around the edge-on spiral galaxy NGC 4013. This arcing feature extends $6'$ ($\sim$ 26 kpc in projected distance) northeast from the center; likely related features are also apparent on the southwest side of the disk, extending to $4'$ ($\sim$ 17 kpc). The detection of this loop-like structure is independently confirmed in three separate datasets from three different telescopes. We estimate a surface brightness of $\mu_{\rm B} = 28.6^{+0.6}_{-0.4}$ mag/$\square''$ and $\mu_{\rm R} = 27.0^{+0.3}_{-0.2}$ mag/$\square''$. The significantly redder colour of the stream material compared to the outer parts of the disk of NGC 4013 suggests that this loop did not originate from the disk itself, but rather is the tidal stream of a dwarf galaxy being destroyed in NGC 4013's gravitational potential. Although its true three-dimensional geometry is unknown, the projected tidal loop displays a very good overall match with the external edge-on perspective of the Monoceros tidal stream in the Milky Way predicted by recent N-body simulations (Peñarrubia et al. 2005). Our results demonstrate that NGC 4013, previously considered a prototypical isolated disk galaxy, is in fact undergoing a tidal encounter with a low-mass satellite. In this sense NGC 4013,

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with one of the most prominent H I warped disks known but showing no previously obvious indication of tidal activity, could be a Rosetta Stone for understanding disks that appear almost pristine in the optical but warped in H I maps and may provide key insights into the formation of warps in general.

Subject headings: galaxies: individual (NGC 4013) — galaxies: dwarf — galaxies: evolution — galaxies: interactions —galaxies: disk galaxies —galaxies: warps

1. INTRODUCTION

In the last decade, the study of the formation and evolution of the Milky Way (MW) has been revolutionized by the first generation of wide-field, digital imaging surveys. The resulting extensive photometric databases have revealed for the first time the existence of spectacular stellar tidal streams (e.g., that from the Sagittarius dwarf galaxy; Ibata et al. 2001a; Martínez-Delgado et al. 2001; Majewski 2003) as well as large stellar sub-structures in the halo (Newberg et al. 2002; Rocha-Pinto et al. 2004; Juric et al. 2005), interpreted as the fossils of the hierarchical formation of our Galaxy. The discovery of the Monoceros tidal stream (Newberg et al. 2002; Yanny et al. 2003), located close to the Galactic plane outside the MW disk (as well as similar structures seen around the M31 disk, Ibata et al. 2005), indicates that mergers might play a relevant role in the formation of the outer regions of spiral disks (Peñarrubia et al. 2006) like that of the MW. Moreover, inside-out disk formation from continual accretion of in-falling material is an observed feature in cold dark matter (ΛCDM) simulations of the growth of structures on galaxy-sized scales (e.g., Abadi et al. 2003), and is now also a common feature of galactic chemical evolution models (e.g., Alibés, Labay, & Canal 2001; Chiappini, Matteucci, & Romano 2001) attempting to explain trends in disk chemical abundance patterns. These various results provide clear evidence that the destruction of satellite galaxies plays a relevant role not only in the formation of MW-like spiral galaxies generally, but for their disks as well as their halos. Furthermore, these results suggest that the stellar mass assembly of the MW disk, and disks in general, likely continues actively to the present epoch.

The search for extragalactic analogues to MW minor mergers is required not only to (1) show that the MW is not unusual in this respect, but to (2) obtain externally-viewed "snapshots" of different phases of such interactions, (3) explore the range of possible mass/orbit combinations for such activity, and (4) estimate the fractional contribution of accreted mass and the mass spectrum of such events in the life of MW-like systems, an issue that remains unresolved (Majewski 1999). In this way, a systematic survey of tidal streams around other, nearby disk galaxies can provide new constraints and insights on the hierarchical formation and structure of MW-like galaxies beyond the previously limited views afforded by our own Galaxy and M31 (Ibata et al. 2007). A need to build up statistical information on the number and distribution of tidal streams in galaxies is driven by the availability of state-of-the-art, high resolution cosmological simulations that offer, for the the first time, the opportunity to use these observations to probe the theoretical predictions of galaxy formation in the framework of the ΛCDM paradigm (e.g., Bullock & Johnston 2005).

Promising galaxies in the hunt for extragalactic tidal streams are those displaying outstanding asymmetries in optical or H I images. It has been long suggested that these perturbations are a result of gravitational interaction with nearby companions. In some cases, apparently isolated galaxies exhibit morphologies more commonly associated with interacting systems. Recently, the prototypical isolated, warped disk galaxy, NGC 5907, was found to be surrounded by a spectacular stellar tidal stream (Shang et al. 1998; Martínez-Delgado et al. 2008), but one with no obvious companion (which may have been completely disrupted). In the case of both the MW and M31 there are also obvious disk warps — both stellar and gaseous — but no immediately obvious perturber, though small, nearby, likely tidally disrupting companion satellites have been suggested as a cause in each case — (Sato & Sawa 1986; Ibata & Razoumov 1998; Bailin 2003; Bailin & Steinmetz 2004). These examples suggest that spirals with warped disks but no large nearby companions, may have undergone *minor* mergers in the last Gyrs.

Under this prepense, we have been observing disk galaxies to faint surface brightnesses in the search for evidence of minor mergers. We (Martínez-Delgado et al. 2008) have previously reported our observations of the debris of a minor merger around the NGC 5907 disk system. Here we report similar work on the edge-on disk, NGC 4013. NGC 4013 is one of the 62 luminous ($M_B < -16.9$) members of the Ursa Major cluster of galaxies, a nearby, late-type dominated, and low mass galaxy cluster. According to the HYPERLEDA database, the mean heliocentric radial velocity of NGC 4013 (836 $\mathrm{km\,s^{-1}}$) places it at a distance of 14.6 Mpc. It is also a relatively isolated system, with the two nearest, slightly more luminous, cluster neighbours (NGC 4051 and NGC 3938) at $\sim$ 170/250 kpc projected distance away. Classified as an Sb galaxy with a maximum observed rotational velocity of 195 $\mathrm{km\,s^{-1}}$ (Bottema 1996), an extinction corrected total absolute magnitude of -20.1 $M_{\mathrm{abs}\,B\mathrm{band}}$ Verheijen & Sancisi (2001), and an optical scale-length of 2.8 kpc ($40''$) (van der Kruit & Searle 1982), NGC 4013 is very similar to the Milky Way. NGC 4013 is, moreover, famous for its prodigiously warped H I disk, with a line of nodes close to parallel with that of the line of sight and with one of the largest warp angles observed ($\sim$ 25 deg). On one side the warp extends out to about 8 kpc ($2'$) from the nominal plane (Bottema et al. 1987; Bottema 1995, 1996). The box/peanut shaped bulge of NGC 4013 with its 'X'-like morphology indicates the presence of a bar being observed edge-on (Patsis & Xilouris 2006).

Here we report the optical detection of a faint, low-surface brightness, loop-like structure that appears to be part of a giant, low-inclination stellar tidal stream of a disrupted dwarf satellite looking very similar to the expected form of the Monoceros tidal stream. This looping structure suggests the likelihood of there having been a previous interaction of NGC 4013 with a low-mass companion. Given the fact that NGC 4013's very prominently warped H I layer matches in shape and orientation those of the apparent tidal loop makes this galaxy system a very compelling example of the likely link between disk warps and mergers, and an interesting case study for models of warp formation.

2. OBSERVATIONS AND DATA REDUCTION

We observed NGC 4013 with three different telescopes and instruments. In each case the same structures appeared, albeit with different degrees of clarity.

2.1. KPNO 0.9-m Telescope

NGC 4013 was initially observed with the Kitt Peak National Observatory (KPNO) (now WIYN) 0.9-m, f/8 telescope as part of a pilot survey of low surface brightness features (like stellar tidal streams) around warped, nearby disk galaxies by C.P. and S.R.M. The initial sample included NGC 3044, NGC 3079, NGC 3432 and NGC 4013, all edge-on systems of large angular size with H I warps but no nearby, massive companions (though, in the cases of NGC 3432 and NGC 3079, some associated or nearby low surface brightness or dwarf satellites). These disk systems resemble NGC 5907, which at the time of this pilot survey had already shown to have a tidal loop by Shang et al. (1998), and, in the case of NGC 3044, a minor merger was already hypothesized (Lee & Irwin 1997). Prior to the sample selection, we used the image filtering technique of Armandroff et al. (1998) on DSS2 images of several nearby, edge-on, warped disk galaxies to search for low surface brightness features indicative of potential streams. The image produced in this way of NGC 5907 does reveal the brightest regions in that stream, however it is at extremely low signal to noise. The target galaxies for the KPNO observations were partly chosen because of structures in the filtered Digitized Sky Survey II (DSS2) images suggestive of potential streams, but in each case these were very low signal to noise features that did not provide incontrovertible proof of such a stream.

The observations were made with the Mosaic camera during several nights (UT 2000-03-31 to 2000-04-04) using the "BATC 9" filter — essentially a narrow version of the Cousins R band — used by Shang et al. (1998) in their imaging of NGC 5907; the filter was kindly loaned by Rogier Windhorst. The conditions for this KPNO run were photometric, with a typical seeing of $\sim 1.3\,''$. Using standard IRAF procedures for the overscan/bias correction and flat-fielding, we combined the final image (see upper panel of Fig.1) of NGC 4013 from the sum of four 1200 sec exposures, eight 1800 sec exposures, and one 900 sec exposure.

A very faint arc is clearly identified in this image, situated at $\sim 26'$ northeast of the center of the galaxy in the region of the extreme of northern plume of the gaseous warp (Bottema 1996, see Sec. 4). However, as may be seen, the achievable flat-fielding and surface brightness limit was not adequate to make definitive conclusions about the nature of this structure.

2.2. Isaac Newton Telescope

To confirm and better trace the extent of this structure, follow-up observations were obtained with the 2.5m Isaac Newton Telescope (INT) at La Palma using the Wide Field Camera (WFC) at f/3.29. This instrument holds four $4096' \times 2048'$ pixels EEV CCDs with a pixel size of $0.332''$, providing a total field of about $35' \times 35'$. Images were acquired during two service nights (UT 2003-03-27 and 2003-04-03) using the Sloan r' (#214) and Harris B (#191) filters. From the first night we have two 600 s r' band exposures and from the second night three additional 600 s r' band images plus four 1350 s B band exposures.

The central CCD (chip 4) was large enough (FOV $22.8' \times 11.4'$) to include NGC 4013 and its warp, so we reduced only chip 4 in isolation, using standard IRAF procedures for the over-scan/bias correction, flat-fielding, and combining of the individual images. The background on the final B band image turned out to be reasonably flat, but the R band exposures suffered from scattered light causing large-scale variations in the background of the order of 2%. After careful masking of all sources, which were replaced by the mean of a linear interpolation along lines and columns, we used the IRAF imsurfit routine on a median filtered ($\sim 30''$ window) version of the masked and interpolated image to determine the background on each individual one. After subtracting this second order fit from the images they were combined to the final r' band version. The two images used in this study have an equivalent exposure time of 50 min for the r' band and 90 min for the B band. Due to the unstable weather conditions (high humidity, sometimes cirrus) during the two nights we did not use the observed standard stars, but obtained our photometric calibration from the r' and g' band Sloan Digital Sky Survey (SDSS) (York et al. 2000) by means of aperture photometry. After geometrically mapping the INT and SDSS images to the same scale and center and applying an identically-sized, but conservative (i.e. large) mask on the disturbing, bright star close to the center of NGC 4013, we obtained fluxes in six concentric apertures

(40″-240″diameter) on all four images and so obtained the photometric zero-points for our INT images. The uncertainty is of the order of 0.01 mag. Following Smith et al. (2002) we converted the SDSS system to Cousins R and Johnson B and all the following magnitudes are given in R and B, correcting for Galactic extinction, ($A_B = 0.072$, $A_R = 0.044$; Schlegel et al. 1998), but not for inclination.

The final image of NGC 4013 is shown in the lower panel of Figure 1. Although the background is still an issue we can now more confidently trace and measure the low surface brightness arc.

2.3. Black Bird Remote Observatory Telescope

Finally, we obtained very deep images of NGC 4013 with the f/8.3 Ritchey-Chretien 20-inch telescope of the Black Bird Remote Observatory (BBRO) situated in the Sacramento Mountains (New Mexico, USA) during different dark sky observing runs in the period UT 2006-11-06 though UT 2006-12-28. We used a Santa Barbara Instrument Group (SBIG) STL-1110 CCD camera, which yields a large field of view (27.7′ x 18.2′) and a plate scale of 0.45 ″pixel^{-1}. These data consist of multiple deep exposures through non-infrared clear luminance ($3500 < \lambda < 8500$) and red, green and blue filters from the SBIG custom scientific filters set[1]. The images were reduced using standard procedures for bias correction and flat-fielding. To enhance the signal-to-noise of the faint structures around NGC 4013, the image noise effects were filtered by means of a Gaussian blur filter (Davies 1990). The final image of NGC 4013 is shown in Figure 2. We have added the labels A through G to identify some photometric feature we discuss in the following Section.

3. THE TIDAL STREAM(S) OF NGC 4013

In addition to the well known peanut-shaped bulge (van der Kruit & Searle 1982, feature A in our Fig. 2) with a full vertical extent of about 2 kpc (30″), a contour plot of the INT image (Fig. 3) reveals a huge, at least 13 kpc (> 3′) sized box-shaped outer "stellar halo" (feature B in Fig. 2 and also obvious in the images in Fig.1). Furthermore, to the East, a striking horseshoe-like structure (feature C in Fig. 4) is visible in the BBRO image, starting at the northeast corner of the box-shaped halo and reaching out to at least 26 kpc (6′) from the center. This feature, that corresponds to the arc detected in the KPNO and INT images

[1]http://www.sgi.com/products/cs-lrbc-filter-curves.htm

(see Sec. 2 and Fig.1), is now evident as loop-like. The obvious hole in the light distribution clearly shows that this feature is not simply a stellar warp, but an actual "ring-like" structure seen obliquely, and of the type produced by tidal streams (see Sec. 4). The loop apparently enters the galaxy again at the southeast corner of the box (labeled F in Fig. 2).

The BBRO and INT images also show a pair of "wings" jutting to the west and southwest (features D and E) and straddling this side of the NGC 4013 disk, "squaring off" the most diffuse galaxy light distribution at large radii. In the diffuse light visible in the northwest edge of the galaxy (feature E), there is some evidence for a shorter, coherent loop feature visible in a high-contrasted version of the BBRO image (Fig. 4). This is consistent with the presence of a second arm of debris (as expected in theoretical simulations, see Sec. 4), which is probably related to the northeast loop (feature C). However, deeper images are necessary to confirm this hypothesis. The more plume-like feature visible on the southwest side (feature D in Fig. 2) extends ~ 17 kpc ($4'$) out. Unfortunately, the clarity of this feature (also barely visible in the INT image in Fig. 1) is somewhat hindered by the presence of two bright stars.

Together, these wings, and the obvious loop to the northeast could be seen as parts of one continuous "ribbon-bow" or "pretzel-like" structure surrounding the disk but with arms that cross each other at the galaxy center(at least in projection). Evidently, these particular features of the extended light distribution are the result of a single, coherent tidal disruption event, which is creating a low-inclination stellar stream around the disk of NGC 4013. An example of how such a tidal structure might be formed is shown in a tidal disruption model (see Figure 5 and discussion in Section 4). It is worth noting that we do not observe any bright spot that could be identified with a remaining, intact dwarf galaxy core among any of the low-surface brightness features. Therefore, our images do not provide any evidence on the final fate of the progenitor galaxy, which could be hidden inside the disk or could be completely disrupted by now.

The surface brightness of the described structures is very close to the present artificial features in the background of our CCD images, which makes it extremely difficult to determine accurate surface brightnesses. Using a set of small $\approx 4''$ boxes, strategically placed along the stream by avoiding stars and any residual obvious brightness condensation, we estimated the mean surface brightness of the stream on the east side (feature C) to be about $\mu_{\rm B} = 28.6^{+0.6}_{-0.4}$ and $\mu_{\rm R} = 27.0^{+0.3}_{-0.2}$. The large errors are due to the uncertainty of $\sim 0.1\%$ in the local sky determination (a set of similar small boxes placed outside, but close to the stream) and are of the same order as the brightness variation along the stream. This yields a $(B-R)$ colour of 1.5 ± 0.8, which is a typically red value found for S0 galaxies (e.g. Barway et al. 2005), and is consistent with the redder dwarfs of the Local Group (Mateo

1998). The colour of the loop is about 0.5 mag[2] redder than the outer (radially/vertically) parts of the disk/halo of NGC 4013. Only close to the mid-plane of the galaxy, where the dust lane certainly reddens the intrinsic colours, we find similar colours as for the stream. This significantly redder colour indicates that its stellar population is not composed of the same mix of stars found in the outer region of NGC 4013's disk, which suggests that this horseshoe-like feature did not originate in the disk itself.

The width of this giant stream is variable along its path, but this may be due to a projection effect. A rough estimate for the FWHM of the stream 1.0 ± 0.3 kpc ($\sim 14''$) is taken at the most distant part on the northeast side of feature C in Fig. 2.

Figure 6 shows the position of the possible tidal stream with respect to the prominent H I gas warp (Bottema et al. 1987; Bottema 1996). This comparison clearly shows that there is no H I gas associated with the detected giant stellar feature (such as is the case in NGC 3310; Wehner & Gallagher 2005) on the northeast side (feature C). On this side, the projected path of the stream shows a very similar inclination to the warped gas disk, but is clearly outside and almost enclosing (in projection) the measured H I gas

Interestingly, our high-contrasted version of the BBRO image (Fig. 4) reveals the trace of a spike-like feature in the northeast edge of the galaxy disk (feature G), with a position and orientation with respect to the galactic plane that is consistent with the stellar counterpart of the prodigious gaseous warp. It is clear, however, that (at our surface brightness limit) this stellar component warp is significant less extended than the H I-component displayed in Fig.6. On the southeast side the extended optical feature D (see Fig. 2) seems to be associated to the southern H I gas plume of the warp, although on this side we are severely hampered by the two bright foreground stars. However, the clear separation of the H I gas and the optical light on the other side of the galaxy let us reject the direct association of these structures as an extended, low luminosity stellar counterpart of the warped H I disk of NGC 4013.

4. DISCUSSION

Our deep images of NGC 4013 show a complex stellar halo, including a coherent, stream-like structure inclined ~ 25 deg with respect to the galaxy disk. We have independently confirmed the presence of these low surface brightness features with three data sets from

[2]Note, the absolute error in the colour is large but the relative colour differences are much less affected by the sky subtraction.

three different telescopes. In addition, if one knows what to look for, the loop is also barely visible on the DSS2 blue plate and on the archival 4.5μ Spitzer Infrared Telescope Facility image. The existence of the loop structure is therefore without question. The discovered structures are evidently debris material produced by the tidal disruption of a low-mass galaxy companion to NGC 4013: Such features are expected from tidal disruption of a companion galaxy (Johnston et al. 2001) and similar features are also observed in NGC 5907 (Shang et al. 1998; Martínez-Delgado et al. 2008), NGC 3310 (Wehner & Gallagher 2005), and a handful of other external galaxies (summarized in Martínez-Delgado et al. 2008, Table 1).

The sky-projected geometry of this structure is in fact remarkably similar to an edge-on, external perspective of the Monoceros tidal stream that the N-body simulations of Peñarrubia et al. (2005) predict, as shown in Fig. 5. In this simulation, the structure is generated from the accretion of a low-mass satellite (6×10^8 $M_\odot$) orbiting in an almost circular (e=0.10±0.05), low inclined ($i \sim 25°$) orbit in the last 3 Gyr. In order to constrain the orbit and mass of the NGC 4013 stream progenitor, more comprehensive N-body simulations that explore the space of free-parameters are necessary. However, the edge-on perspective of NGC4013 is useful to constrain at least one parameter, the orbital inclination, which can be simply derived from Fig.2 by comparing the maximum vertical deviation from the disk plane versus its radial extension. From this Figure one can readily check that $Z_{\max}/R_{\max} \approx 0.43$, so the orbital inclination of the stream progenitor is approximately $i \approx \mathrm{atan}(Z_{\max}/R_{\max}) \simeq 23°$. This value is practically the same as that of the Monoceros stream progenitor (i=25° ± 5° Peñarrubia et al. 2005).

The similarities between the stream in NGC 4013 and the model of Peñarrubia et al. (2005) can also be used to estimate the stream age. NGC 4013 has a smaller disk scale-length, $h_R = 2.8$ kpc, and a lower maximum circular velocity, $V_{c,\max} = 195$ km s^{-1} (Bottema 1996) than the Milky Way. Using dynamical considerations we can write that $\mathrm{Age}/\mathrm{Age}_{Mon} = h_R/h_{R,MW} \times V_{c,\max}/V_{c,\max,MW}$. For the Milky Way we have that $h_R = 3.5$ kpc and $V_{c,\max} =$ 220 km/s, thus $\mathrm{Age}/\mathrm{Age}_{Mon} \approx 0.9$. Since some pieces of the Monoceros stream are $\mathrm{Age}_{Mon} =$ 3 Gyr old, we estimate that the stream surrounding NGC 4013 may be as old as $\simeq 2.8$ Gyr.

While not claiming that the model shown is an accurate representation of the true mass, satellite brightness, age, orbit, etc. of the NGC 4013 interaction, the morphological similarity of the model results to the observed structures seen in NGC 4013 lends considerable support to the claim that the full extent of the diffuse light structures we observe for NGC 4013 can plausibly be explained as part of a coherent, tidal stellar stream from a single satellite moving on a low-inclined, low-eccentricity orbit during the last few Gyrs with an initial mass of the order of $\sim 5 \times 10^8 M_\odot$.

However, despite the same model is able to reproduce the geometry and extent of both streams, the observed surface brightness of the one surrounding NGC 4013 is startlingly higher (approximately ∼5 magnitudes) than the value reported for the Monoceros tidal stream ($\mu_B \sim 34.0$mag/□″ Martínez-Delgado et al. 2008). A possible explanation might be that the progenitor of the NGC 4013 stream was more luminous than that of the Monoceros stream. Since both models have the same initial mass this would imply that the mass-to-light ratio of the NGC 4013 stream progenitor was considerably lower than that of the Monoceros stream. However, this is only true for models that assume the same spatial distribution for stars and dark matter (mass-follows-light models), which are not supported by the present cosmological paradigm. In a ΛCDM cosmogony, stars only populate the inner-most regions of dwarf galaxies Strigari et al. (2007); Penarrubia et al. (2007) and can only be tidally stripped after most of the dark matter halo beyond the luminous radius has been lost Penarrubia et al. (2007). These models introduce a new parameter: the spatial segregation of the stellar component with respect to the surrounding dark matter halo of the progenitor galaxy, which is fundamental to determine the survival time of dwarf galaxies and the properties of their associated tidal streams Penarrubia et al. (2007). For example, the more deeply embedded within the halo a stellar component is, the thinner, brighter and colder will be its associated tidal stream. Therefore, for ΛCDM-motivated models, the halo size, the stellar spatial segregation and the total luminosity of a dwarf galaxy are all parameters that influence the resulting surface brightness of an associated tidal stream. Unfortunately, in absence of additional data (e.g. kinematics) these parameters cannot be tightly constrained and it is therefore unclear what might cause the strong difference in surface brightness between the Monoceros and NGC 4013 tidal streams.

The discovery of this giant stellar stream shows that the outskirts of nearby spiral galaxies still contain the fossils from their hierarchical galaxy formation, in agreement with the expectations within the cosmological models obtained in the ΛCDM paradigm (e.g., Bullock & Johnston 2005), where the galaxies are built up inside-out by the accretion of smaller subsystems (e.g., Abadi et al. 2003). In this context, the existence of low-inclined tidal streams that could reshape the outer regions of our Galaxy (e.g., the Monoceros or Triangulum/Andromeda tidal streams, Yanny et al. 2003; Majewski 2003; Grillmair 2006; Peñarrubia et al. 2008) is still controversial, mainly due to the limited available models of the MW structure and the severe extinction hindering exploration of these parts of our Galaxy. Although the detection of this stream around NGC 4013 cannot prove the existence of low-latitude streams in the MW, it provides a comprehensive, external perspective of such kind of tidal structures, and demonstrates that they may not be so rare around spiral galaxies. In fact, their occurrence in the known sample of stellar tidal streams in the Local Volume ($D < 15$ Mpc; see Martínez-Delgado et al. 2008; Pohlen et al. 2004) is $\gtrsim 20\%$. The presence of giant disks around spiral galaxies that extend out to several scale-lengths of the inner disk (e.g. the extended disk found by Ibata et al. (2005) around M31 is detectable out to a projected radius of 80 kpc with the present instrumentation) might be a result of the accretion of massive satellite galaxies moving on low-inclination, low-eccentricity orbits (Peñarrubia et al. 2006), adding support to the scenario that the disks of spiral galaxies may grow inside out as a result of this type of accretion events.

The detection of galactic warps in spiral galaxies that present signatures of recent accretion events is quickly increasing with the availability of wide-field, deep photometric surveys. Although the origin of galactic warps is still unknown, it was early proposed that the gravitational perturbations induced by satellite galaxies may cause the formation of warps (Burke 1986, although see Hunter & Toomre 1969 for counter-arguments). Since those early studies, several alternative scenarios have been proposed in the literature. For example, it has been shown that the interaction of a stellar disk with the surrounding dark matter halo may also induces the formation of warps (Sparke & Casertano 1988; Binney et al. 1998), as well as bending instabilities (Revaz & Pfenniger 2004), intergalactic accretion flows onto the disk (López-Corredoira et al. 2002) and cosmic in-fall (Shen & Sellwood 2006). A crucial fact that has been often invoked to dismiss the tidal origin of galactic warps was the existence of warped spiral galaxies in apparent isolation (Sancisi 1976). NGC 4013, with its prominent, and rather symmetrical H I warp, along with a really unassailable indication of a past merger event, provides an important counter-example to the above argument; indeed, NGC 4013 may well be the Rosetta Stone for warp theories, since morphologically the warp and the merger debris seem so closely aligned.

With NGC 5907 and NGC 4013 we have now two examples of apparently isolated galaxies with significantly warped gaseous disks, which at the same time show evidence for an ongoing tidal disruption of a dwarf companion. The connection between the warp of the MW and its satellite galaxies has been already explored in some recent studies. For example, Bailin (2003) and Weinberg & Blitz (2006) study the effects of the Sagittarius dwarf and the Magellanic Clouds on the MW disk, respectively. Interestingly, the existence of warped galaxies that have suffered a recent accretion of satellite galaxies on low-inclination, low-eccentricity orbits (like the MW and NGC 4013) suggests that these kind of accretion events may induce the formation of warps more efficiently than the perturbations from satellite galaxies moving on highly eccentric, nearly-polar orbits. This is a possibility worth to be further investigated.

With the growing numbers of examples showing a connection between warped disks and evidence of mergers, even for disk systems with no obvious companions, we may be close to resolving the mystery of warps, and in a way be consistent with prevailing ΛCDM models of galaxy formation.

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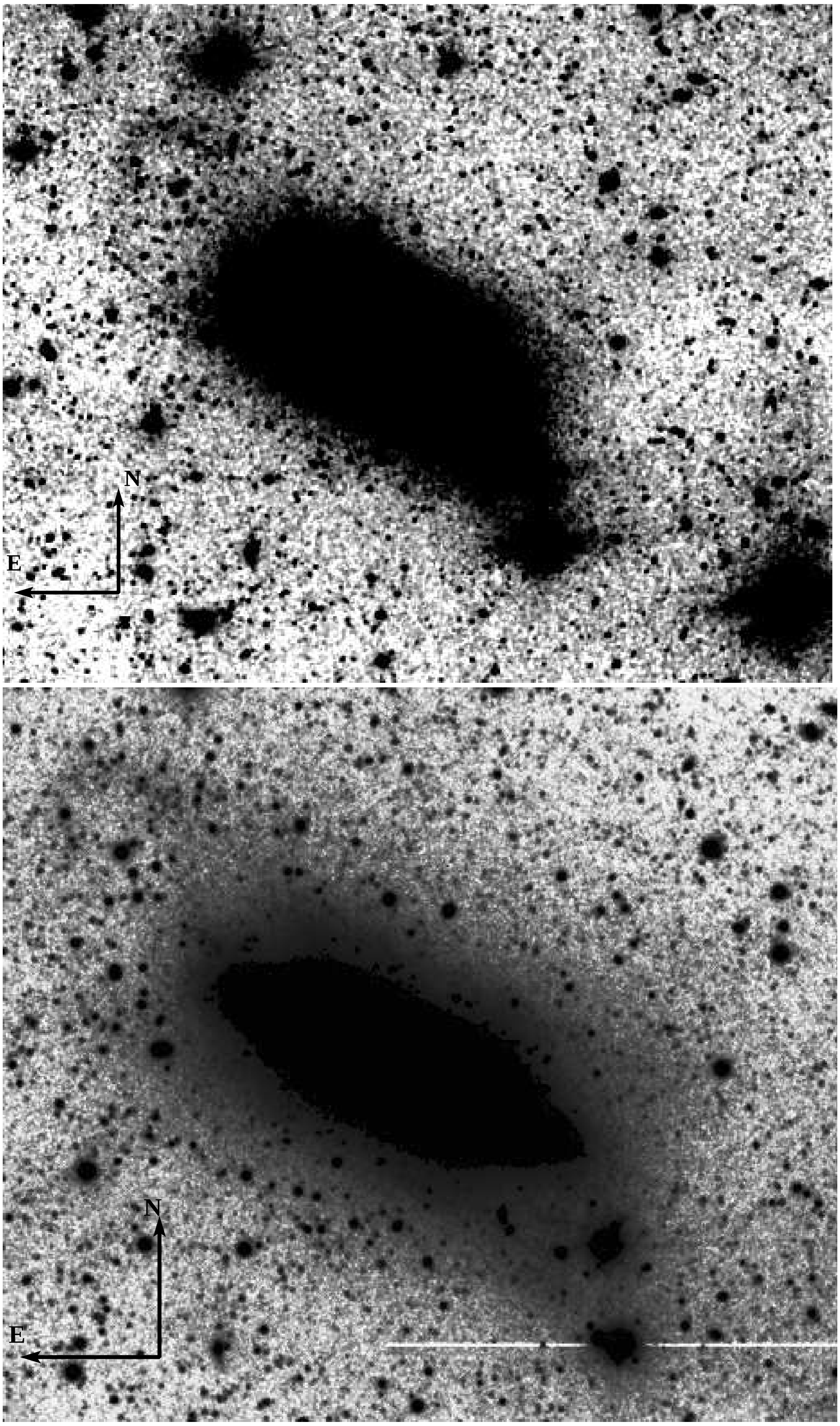

Fig. 1.— NGC 4013: Smoothed and enhanced versions of the KPNO 0.9-m image *(upper panel)* and the INT B band image *(lower panel)* highlighting the low-surface brightness features. The arrows of lengths 2′ in the lower left corner give the size and orientation.

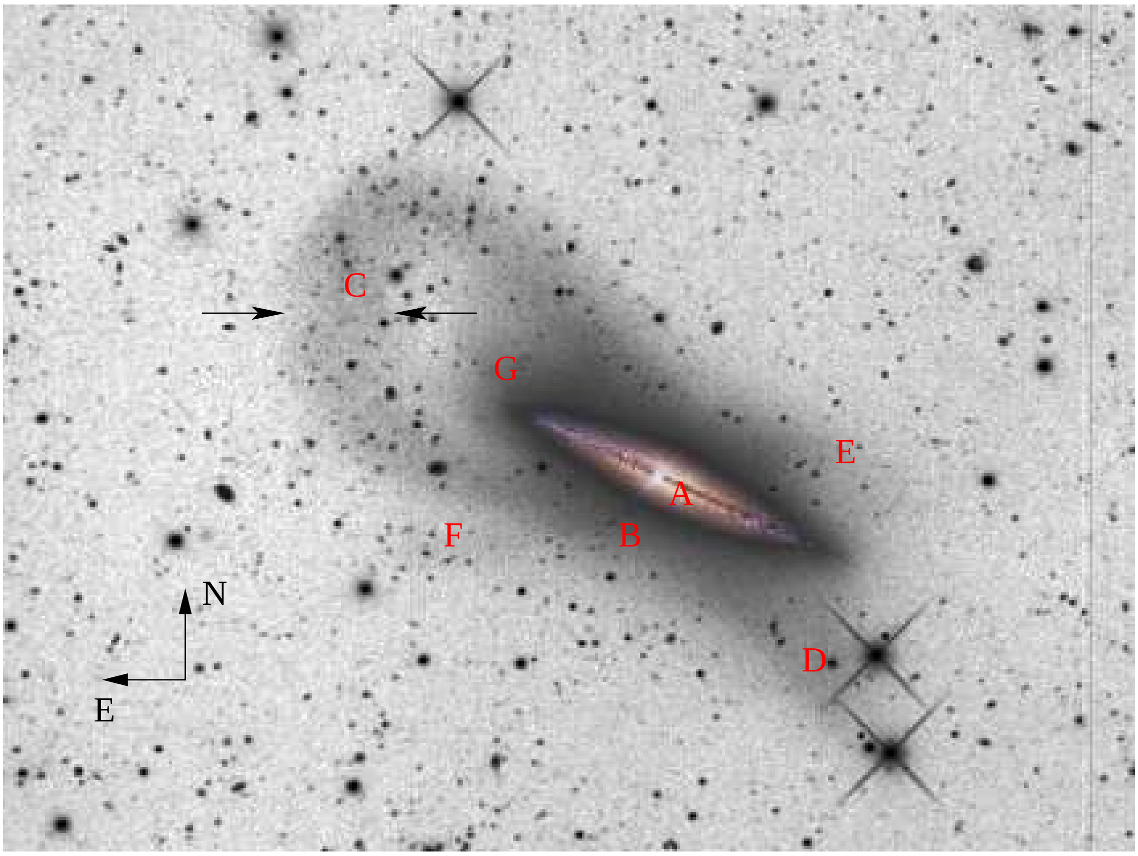

Fig. 2.— Image of NGC4013 obtained with the BBR0 20-inch telescope. The total exposure time of the original image was 13.7 hours (including 11 hours in clear-luminance filter) and was noise-filtered by applying a Gaussian blur filter. The image has dimensions of $\sim 18.5' \times 15'$, which, at the distance of NGC 4013 is $\sim 78 \times 63$ kpc. Identified photometric features labeled A-G are discussed in Sec.3. For illustrative purpose, a colour image of the NGC 4013 obtained with the same telescope has been superimposed on the saturated disk region of the galaxy.

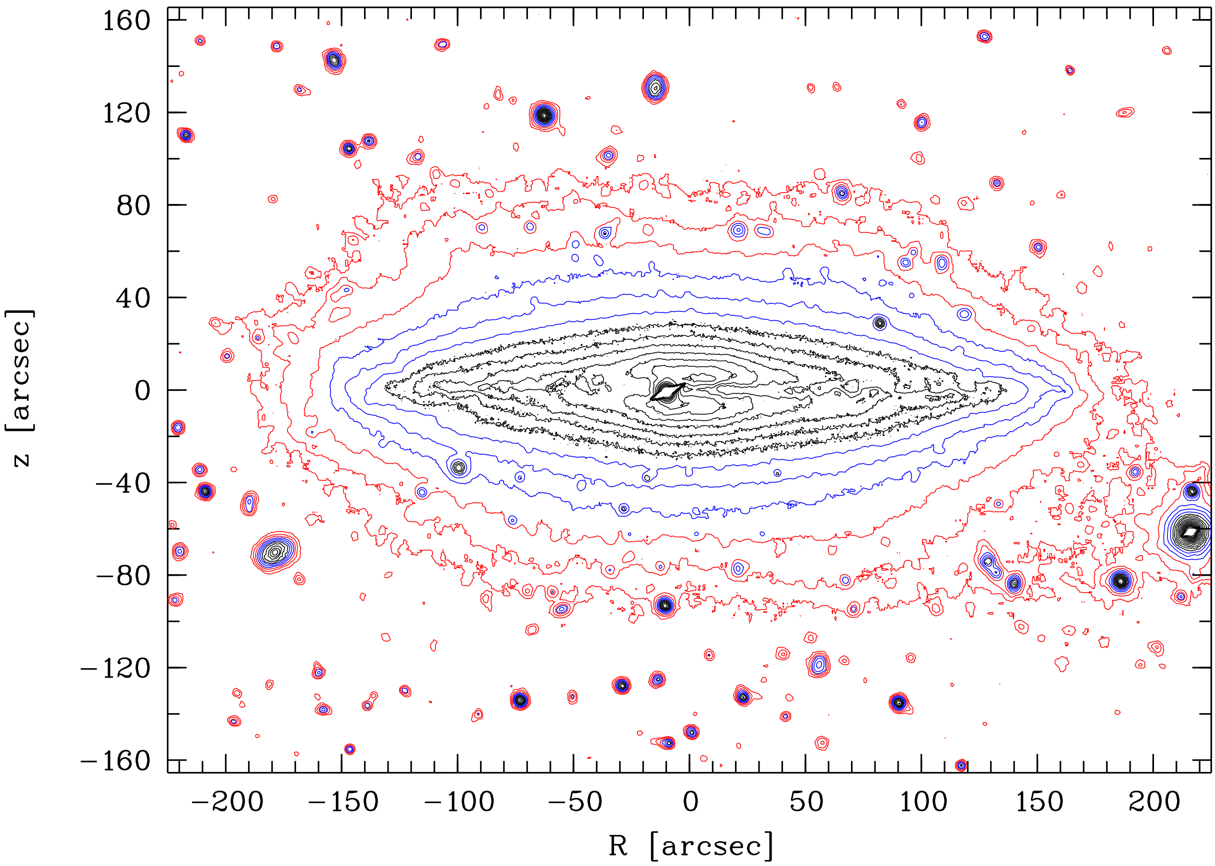

Fig. 3.— Isaac Newton Telescope *B* band contour map of NGC 4013 highlighting the box-shaped outer halo. Contours are at levels 17.0-27.0 B-mag arcsec^{-2} in equidistant steps of 0.5 mag. Towards the outer parts we smoothed the contours using three increasing levels of median filtering (indicated by the three different colours).

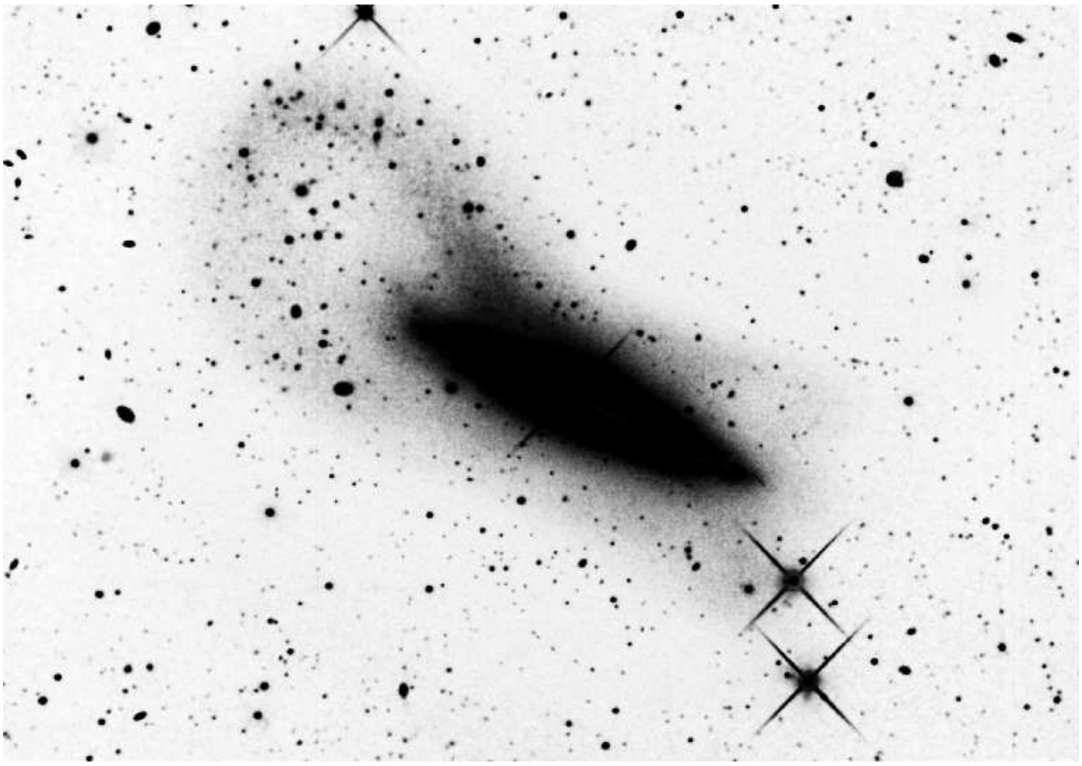

Fig. 4.— A stretched version of the luminance clear-filter image of NGC 4013 obtained with the BBRO telescope. This shows evidence of a possible second arm of debris within the diffuse light wind to the northwest edge of the NGC4013 disk (feature E in Fig.2). In addition, the spike-like feature visible in the northeast edge of the disk could be related to the stellar component of the prodigious gaseous warp of the galaxy. North is up and East to the left.

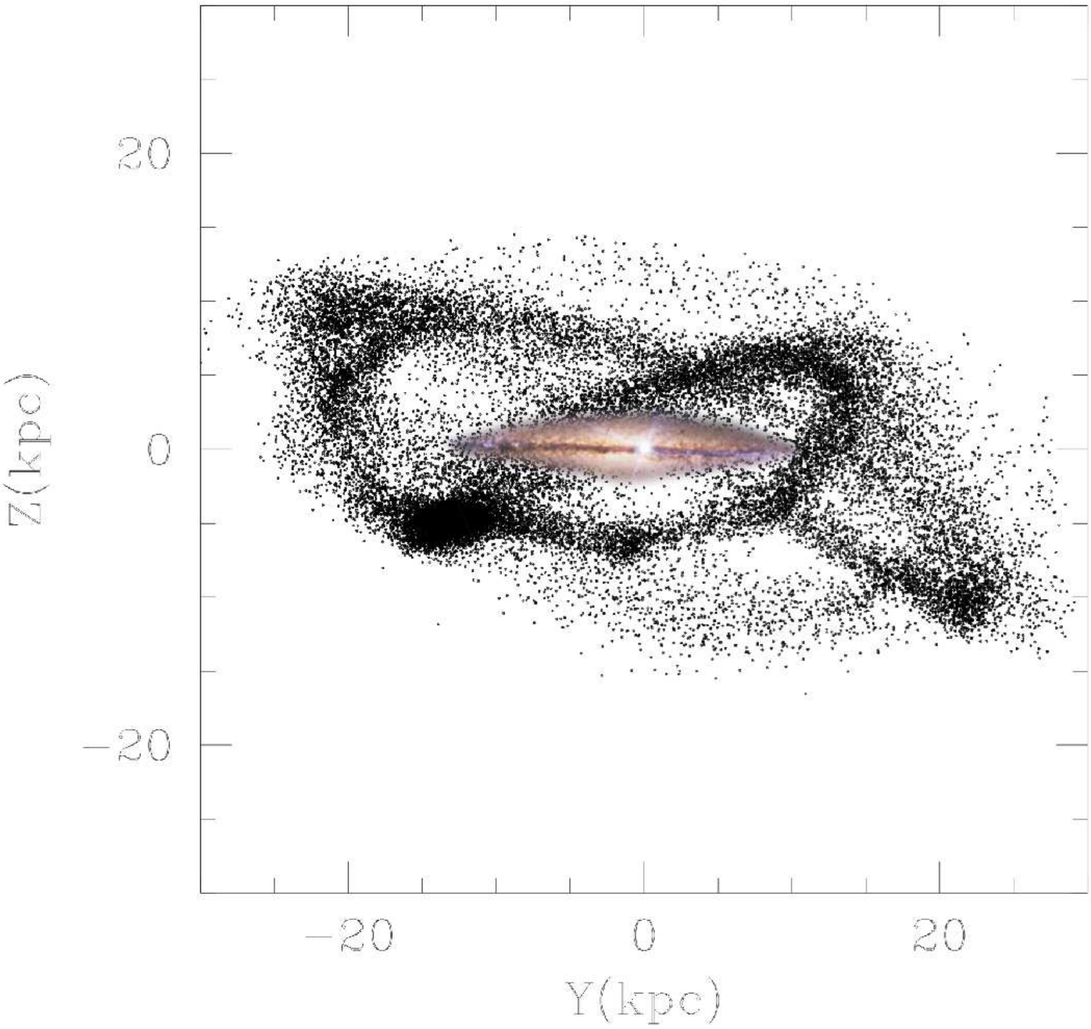

Fig. 5.— X-Y galaxy plane projection of the prograde model *pro1* of the Monoceros tidal stream by Peñarrubia et al. (2005). For comparison purposes, a colour image of the NGC 4013 disk (see Fig.2) has been scaled (assuming a distance of 14.6 Mpc)and superimposed to the distribution of debris. The comparison of this model snapshot to the structures detected in NGC 4013 provides considerable support for the hypothesis that they consist of different pieces from a single tidal stream. The NGC 4013 disk (and the residual light of its box-shaped outer halo showed in Fig.4, not simulated here) almost overlaps the full path of the stream, that emerges as individual loop-like structures of debris (or winds) at large galactocentric radius (features C and E in Fig.2 and 4

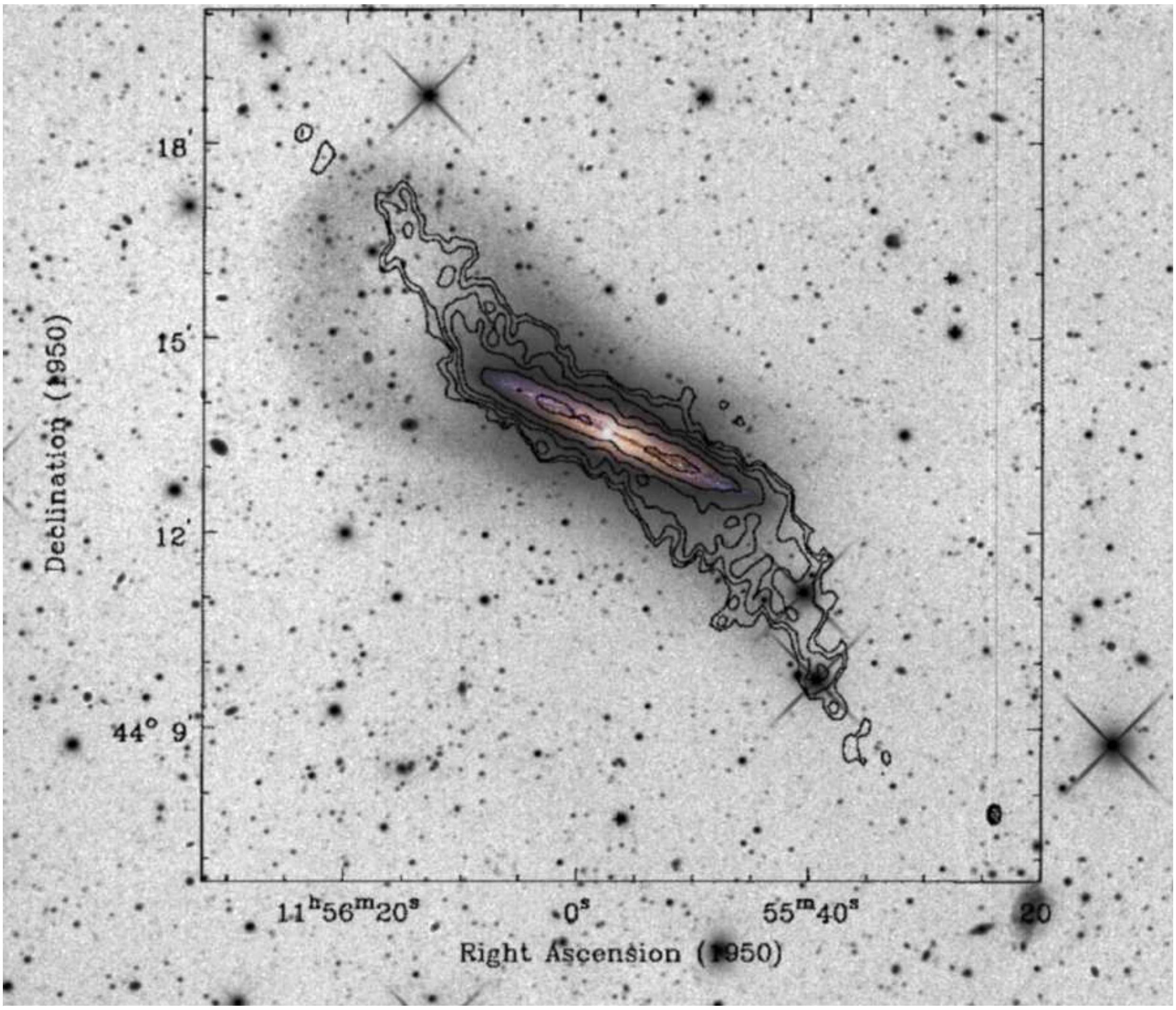

Fig. 6.— Overlay of the H I contours from Bottema (1996) (his Fig.1) on our BBO image of NGC 4013. The lowest H I contour level shown is about 1×10^{20} H-atoms cm^{-1}. The beam is given in the lower right corner of the H I insert. The scale of this image is $\sim$4.2 kpc/arcmin.