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Letter to the Editor

Hanny's Voorwerp*

Evidence of AGN activity and a nuclear starburst in the central regions of IC 2497

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ABSTRACT

We present high- and intermediate resolution radio observations of the central region in the spiral galaxy IC 2497, performed using the European VLBI Network (EVN) at 18 cm, and the Multi-Element Radio Linked Interferometer Network (MERLIN) at 18 cm and 6 cm. We detect two compact radio sources, with brightness temperatures above 10^5 K, suggesting that they are related to AGN activity. We show that the total 18 cm radio emission from the galaxy is dominated neither by these compact sources nor large-scale emission, but extended emission confined within a sub-kpc central region. IC 2497 therefore appears as a typical luminous infrared galaxy that exhibits a nuclear starburst with a massive star formation rate ($M > 5\ M_{\odot}$) of 12.4 $M_{\odot}$/yr. These results are in line with the hypothesis that the ionisation nebula "Hanny's Voorwerp" at a distance of ∼15−25 kpc from the galaxy is ionised by the radiation cone of the AGN.

Key words. galaxies: active – galaxies: ISM – galaxies: individual: IC 2497 – galaxies: star formation

1. Introduction

Hanny's Voorwerp (SDSS J094103.80+344334.2)[1] is an irregular gas cloud located ∼25 kpc to the southeast of the massive disk galaxy IC 2497 (Lintott et al. 2009; Józsa et al. 2009). In the optical, the Voorwerp's appearance is dominated by [O III] emission lines, and its spectrum shows strong line emission, with high-ionisation lines (He II, [Ne V]) co-extensive with the continuum (Lintott et al. 2009). Paradoxically, there is no evidence of an ionising source in the immediate proximity of this nebulosity. Its quiescent kinematics, derived from optical spectra, imply that photoionisation is the predominant ionisation process, rather than ionisation via shocks (Lintott et al. 2009; Józsa et al. 2009). The original explanation of this phenomenon was provided by Lintott et al. (2009), who argued that Hanny's Voorwerp may be the first example of a quasar light echo. It is proposed that around 10^5 years ago, IC 2497 underwent a significant outburst with its central luminosity approaching quasar-like levels before decreasing to current, lower-levels of activity. In this scenario, observations of the Voorwerp today therefore represent a snapshot of this extreme quasar outburst as it was 10^5 years ago.

Radio observations using the Westerbork Synthesis Telescope (WSRT) and the EVN (using the e-VLBI technique) (Józsa et al. 2009) have detected a radio continuum source at the central position of IC 2497, and weak, large-scale emission pointing in the direction of Hanny's Voorwerp. In addition, neutral hydrogen, presumably debris from a past interaction, is detected around the galaxy. The Voorwerp is probably part of this large surrounding gas reservoir. HI is also detected in absorption towards the central radio core. Obscuring material in the direction of the core of IC 2497 is clearly present, while the extended continuum implies that a large-scale radio jet is present. These radio observations support an alternative to the light-echo scenario, namely that IC 2497 contains an obscured active galactic nucleus (AGN) with a weak, large-scale radio jet pointing in the direction of Hanny's Voorwerp, perpendicular to the major axis of the galaxy (Józsa et al. 2009). Hence, another interpretation of Hanny's Voorwerp is that it is a rare and spectacular example of ongoing AGN feedback in which an obscured AGN at the centre of a relatively nearby galaxy is observed ionising the surrounding IGM (Józsa et al. 2009).

In this Letter, we present new radio continuum observations of the galaxy IC 2497 with the European VLBI Network (EVN) using the e-VLBI technique at 18 cm, and with the Multi-Element Radio Linked Interferometer Network (MERLIN) at 18 cm and 6 cm. The complementary observations, providing on one hand a higher sensitivity at high resolution, and on the other hand probing the ISM on intermediate scales, permit us to investigate the AGN hypothesis and map the central radio emission, which is unresolved in WSRT- and VLBI observations. We argue that our observations confirm the former detection of an

* Table 2 is only available in electronic form at
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[1] "Voorwerp" is Dutch for object.

Table 1. Radio observations of IC 2497.

Epoch	Array	λ (cm)	σ_λ (mJy beam^{-1})	Beam size (mas^2)	PA (°)
2009.092	MERLIN	18	0.037	178×165	19.5
2009.226	MERLIN	6	0.070	100×100	0.0
2009.387	EVN	18	0.015	45×27	7.7

AGN at the centre of IC 2497 and indicate the presence of a strong, central starburst in IC 2497, providing support to the hypothesis that the AGN activity in IC 2497 is obscured towards the observer.

2. Observations and data reduction

In the following discourse, we describe in detail the observations with the EVN and MERLIN, and the subsequent data analysis. A summary of the properties of the derived maps is given in Table 1.

2.1. e-VLBI 18 cm observations

On 19 May 2009 and 20 May 2009, IC 2497 was observed at 18 cm with the EVN using the e-VLBI technique. The experiment was performed using the Westerbork, Medicina, Onsala 25-m, Torun, Effelsberg, Jodrell Bank (Lovell), Cambridge, and Knockin telescopes.

The data were transported to the correlator at the Joint Institute for VLBI in Europe (JIVE) in real-time using the User Datagram Protocol (UDP). The radio telescopes were physically connected to JIVE via the National Research and Educational Networks (NRENs) and the pan-European research network GÉANT2 via the Dutch national research network SURFnet (Garrett 2004; Szomoru 2008). At the time of our observations, a sustainable data rate of 512 Mbps was achieved. For further details we refer to Szomoru (2008).

The target was phase-referenced to J0945+3534 (Beasley et al. (2002), RA = 09:45:38.121 Dec = +35:34:55.089, J2000), a phase calibrator located 1.3 degrees away from the target source IC 2497. A phase-reference cycle time of 7 min (2 min on the calibrator and 5 min on IC 2497) was employed. The data were composed of 8×8 MHz sub-bands (in both left-hand and right-hand polarisations) with 2-bit data sampling at the Nyquist rate, resulting in a total data rate of 512 Mbps. The correlator accumulation period was 2 s and the total observing time was approximately 10 h from UT 14:47:36 to 00:54:37, with ~7 h on-source. The maximum projected baseline amounts to 8 Mλ (Lovell-Medicina). The shortest projected baseline (Lovell-Knockin) is at ~0.35 Mλ, hence structures with an angular size of above ~0.6 arcsec are resolved out (structures with intensity variations above this scale are not detected).

The initial data reduction was performed using the National Radio Astronomical Observatory (NRAO) software package *AIPS*. The data were edited, amplitude-calibrated and fringe-fitted using standard techniques. The calibration information was not complete for all the telescopes, and we expect the absolute flux density scale to be accurate at the ±20% level. The calibration solutions derived from J0945+3534 (including phase and amplitude corrections obtained by hybrid mapping the source) were applied to the target IC 2497 data. The calibrated UV data of IC 2497 were Fourier transformed and the CLEAN algorithm Högbom (1974) was applied using the AIPS task IMAGR. The data were then phase self-calibrated with corrections derived across the entire 64 MHz band in each hand of polarisation and over a solution interval of 10 min. The final, naturally weighted image is shown in Fig. 1.

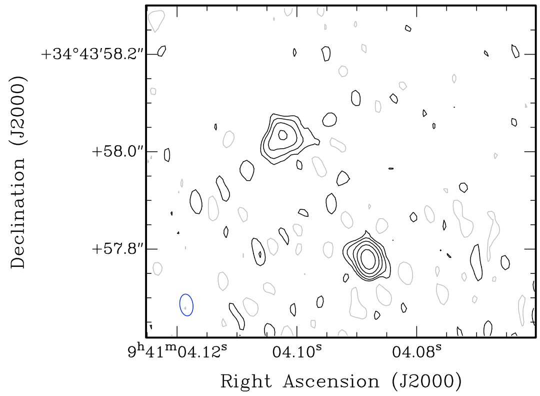

Fig. 1. e-VLBI λ 18 cm radio map of IC 2497, showing both components, C1 & C2. The contours are at −1, 1, 2, 4, 8, and 16 × 0.03 mJy beam^{-1}.

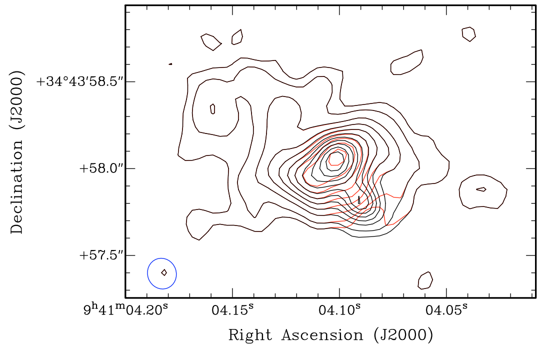

Fig. 2. The naturally weighted λ 18 cm MERLIN radio map of IC 2497 (black contours), showing both C1 and C2, embedded within a region of smooth extended emission, overlaid over the same map with the point sources subtracted (see text, grey contours, red in online version). The contours are drawn at 1, 2, 4, 6, 8, 10, 12, 14, 16, 18, and 20×0.074 mJy beam^{-1}.

2.2. MERLIN 18 cm observations

Additional observations of IC 2497 were conducted with MERLIN at λ 18 cm, using 15×1 MHz channels in all 4 Stokes parameters. The observations were performed in two separate runs, on the 2 February 2009 and 3 February 2009 (16:22–08:59 UT) for approximately 17 h and on the 4 February 2009 and 5 February 2009 (17:17–07:20 UT), with approximately 15 h and 12 h on-source, respectively. The outer 2 frequency channels were deleted due to band-pass effects. The UV coverage for this observation extends to a maximal baseline of 1.2 Mλ. The shortest projected baseline at ~90 kλ corresponds to a spatial scale of ~2.29 arcsec, above which structures are resolved out.

The observations were amplitude-calibrated using 3C 286 (the primary flux-density calibrator) and B2134+004 (a point-source secondary amplitude calibrator). We found B2134+004 to have a flux density of 10.058 Jy. A phase reference cycle time of 8 min was employed (7 min on the target IC 2497, and 1 min on the phase calibrator, J0945+3534, Beasley et al. 2002). The phase solutions derived from J0945+3534 were transferred to the target, IC 2497. No self-calibration techniques were applied to the target data, as the source was very weak and heavily resolved on the Cambridge-Defford baseline. The data were reweighted to reflect the relative telescope sensitivities, in order to optimise the rms noise in the image. The final naturally weighted image is presented in Fig. 2.

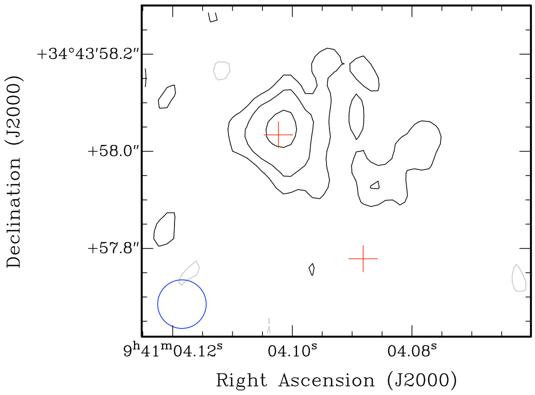

Fig. 3. λ 6 cm MERLIN radio map of IC 2497, showing the component C1. The contours are drawn at −1, 1, 2, and 4 × 0.140 mJy beam^{-1}. The crosses indicate the positions of C1 and C2 as measured from the VLBI map.

2.3. MERLIN 6 cm observations

We observed IC 2497 using MERLIN at λ 6 cm, with 15 × 1 MHz channels in all 4 Stokes parameters. The observations were performed in two 18.5 h runs on 21 March 2009 and 22 March 2009 (12:15−07:00 UT) and 22 March 2009 and 23 March 2009 (12:30−07:00 UT), with approximately 16 h on-source. The maximum UV coverage for this observation, extends to 3 Mλ. The shortest projected baseline covers ~0.27 Mλ, which corresponds to a spatial scale of 0.76 arcsec, above which structures are resolved out. The calibration and analysis followed the same path as the 18 cm observations. The final naturally weighted image, with an additional 2 Mλ Gaussian taper applied to the UV-data, is shown in Fig. 3.

3. Results

Figure 1 shows the the radio image of the 1.65 GHz e-VLBI observation. The image shows two compact radio components, separated by ~300 milliarcsec ($\tilde{\approx}$312 pc)[2]. The component to the southwest (hereafter C1) was initially detected by a short track 18 cm EVN (e-VLBI) observation (Józsa et al. 2009), and to the northeast of C1 is a fainter, newly discovered component (hereafter C2).

The sources appear marginally resolved in the VLBI map but this may be due to residual phase errors after phase referencing. The total integrated flux density measured for C1 is 1.03±0.03 mJy, which is close to the flux density of 1.1±0.1 mJy obtained by Józsa et al. (2009) The total integrated flux density for C2 is 0.61 ± 0.04 mJy. This represents only 10% of the total WSRT and VLA FIRST flux density measurements (20.9 and 16.8 mJy, respectively). Measurements of the size of both components using the AIPS task IMFIT suggest maximum sizes of 44 milliarcsec for C1, and 58 milliarcsec for C2. From this, we determine a limit of the brightness temperature of $T_b > \sim 4 \times 10^5$ K, and $T_b > \sim 1.4 \times 10^5$ K, for C1 and C2, respectively.

In the lower resolution 1.65 GHz MERLIN observation (see Fig. 2), C1 is also shown to be compact, but with a possible slight elongation to the southwest, while C2 shows a lot of extended emission. The extended emission located around C2 has a position angle that is similar to the large-scale major axis of the disk in IC 2497. We measure the peak brightness of C1 and C2 to be 0.88 mJy beam^{-1} and 1.00 mJy beam^{-1}, respectively. The total flux density including both components and the extended emission is 11.9 ± 0.2 mJy, which corresponds to ≈12.8 mJy at 1.4 GHz, using the spectral index of −0.55, from Józsa et al. (2009). Subtracting the flux density of the extended WSRT (large-scale jet-) component ($S_{1.4\,\mathrm{GHz}}$ = 3.2 ± 0.2 mJy, Józsa et al. 2009), from the total WSRT flux density ($S_{1.4\,\mathrm{GHz}}$ = 20.9 ± 1.1 mJy) leaves 17.7 mJy for the central point source as observed by the WSRT. Therefore, ~75% of the emission from the VLA FIRST survey and ~70% of the emission contained in the central, component, unresolved by the WSRT (Józsa et al. 2009), are recovered by the 18 cm MERLIN observation. This suggests that most of the radio flux measured by the WSRT and VLA is associated with the extended emission detected in the MERLIN observations. To help determine of the structure of this extended component, the VLBI CLEAN components were convolved to match the MERLIN (18 cm) resolution, rescaled by a factor of 0.8 to minimise residuals, and subtracted from the MERLIN18 cm map. The resulting residual map is shown in Fig. 2.

We detect only component C2 in the MERLIN 5 GHz observations (see Fig. 3). None of the extended emission associated with C2 at 1.65 GHz is detected. At 5 GHz C2 appears to be slightly extended in the direction of C1 at 18 cm. The component C1 is not detected, placing a 5-σ upper limit on its flux density of 0.26 mJy at this frequency and resolution. The position of C1 detected by the EVN at 18 cm is indicated by the cross in Fig. 3. A summary of the various properties of components C1 and C2 are presented in Table 2.

4. Discussion

Our results support the hypothesis that an AGN is located at the centre of IC 2497. In our 18 cm EVN and MERLIN observations, we have detected 2 distinct radio sources in the central region of IC 2497, (C1 and C2) with measured brightness temperatures in excess of 10^5 K, an upper limit for brightness temperatures of star-forming regions (Condon et al. 1991; Biggs et al. 2010). By tapering the EVN image ($S_{\mathrm{C1\,total,\,2M}\lambda\,\mathrm{taper}}$ = 1.103 mJy and $S_{\mathrm{C2\,total,\,2M}\lambda\,\mathrm{taper}}$ = 0.597 mJy) and comparing with the MERLIN 6 cm map, we derive a relatively flat spectral index ($S \propto \nu^{\alpha}$) $\alpha_{\mathrm{C2}} \sim 0.12 \pm 0.01$ for C2, suggesting that this is the radio core in IC 2497 associated with a central AGN. By comparison C1, has a much steeper spectrum: assuming an upper limit to the flux density of C1 of ~0.26 mJy, we derive a spectral index of $\alpha_{\mathrm{C1}} < -1.38 \pm 0.10$. In this scenario, C1 is most likely a hotspot in the large-scale jet observed on larger scales. Unfortunately, the radio luminosity of C2 tells us very little about the ionising potential of the associated AGN at optical and UV wavelengths. It does however, clearly identify some level of AGN activity in the central regions of IC 2497. The approximate separation of the components C1 and C2 is 300 milliarcsec, with the associated position angle being 215 degrees. Given the different scales involved, this is very similar to the position angle defined by both the direction of the WSRT kpc jet (Józsa et al. 2009) and the Voorwerp itself of ~280 degrees. The extended emission detected by MERLIN at 18 cm and associated with C2 is aligned with the major axis of the galaxy. This extended emission has physical dimensions of ~0.4 kpc. A comparison of the WSRT, MERLIN, and e-VLBI observations suggests that the bulk of the radio emission is extended in nature.

We can estimate the flux density of the radio emission associated with star formation in IC 2497 by subtracting the contribution from both the compact VLBI components and the

[2] We use a redshift-distance of 210 Mpc (Józsa et al. 2009) throughout this paper.

large-scale radio jet detected by the WSRT. This yields a flux density for the extended radio emission associated with the star formation of 15.7 ± 1.1 mJy. This, in addition to the IRAS FIR flux densities of $S_{100\mu}$ = 3.04 ± 0.3 Jy and $S_{60\mu}$ = 1.66 ± 0.2 Jy (Helou & Walker 1988), permits us to calculate a q-value (Condon 1992) of 2.2 ± 0.04. We find that IC 2497 clearly, lies close to the standard FIR-radio correlation for star-forming galaxies, and the sub-kpc scale of the extended emission implies that it is a good example of a nuclear starburst system. It appears that this nuclear starburst is coincident with the AGN core. The luminosity of the extended radio emission implies a massive star formation rate. Using the standard relations given in Condon (1992, 2002) with the implied standard IMFs (Miller & Scalo 1979; Salpeter 1955), we derive a star formation rate $SFR(M > 5\ M_{\odot})$ of 18.1 $M_{\odot}\,\mathrm{yr}^{-1}$ (or $SFR(M > 0.1\ M_{\odot}) \sim 100\ M_{\odot}\,\mathrm{yr}^{-1}$) for the entire galaxy. The star formation rate derived from the central, extended emission detected by MERLIN is $SFR(M > 5\ M_{\odot}) \sim 12.4\ M_{\odot}\,\mathrm{yr}^{-1}$ (or $SFR(M > 0.1\ M_{\odot}) \sim 68\ M_{\odot}\,\mathrm{yr}^{-1}$).

With a FIR luminosity of $1.3 \times 10^{11}\ L_{\odot}$ derived from the IRAS flux densities, IC 2497 lies in the regime of a class of galaxies known as the luminous infrared galaxies (LIRGS). It also shares their characteristics of a nuclear starburst (Sanders & Mirabel 1996), as well as showing clear signs of interaction with the environment (Józsa et al. 2009, see also below). This nuclear starburst is likely to be responsible for significant obscuration of the central AGN along our line-of-sight (Sanders & Mirabel 1996). The enhanced level of star formation in IC 2497 is also presumably associated with the infall of gas due to previous interactions with neighbouring galaxies in the field, which is assumed in general to be the origin of the enhanced star formation in LIRGS (Sanders & Mirabel 1996). This interaction would induce large-scale non-circular motions that could transport gas to the central regions, fueling both the nuclear starburst and AGN activity simultaneously in IC 2497.

Another consequence of past-interactions, is the creation of a huge debris reservoir of HI gas around the galaxy, as observed by the WSRT. We propose that Hanny's Voorwerp corresponds to the part of the debris trail that is illuminated by the AGN illumination cone (and indeed the nuclear starburst). The line-of-sight between Hanny's Voorwerp and the nuclear region of IC 2497 is roughly perpendicular to the plane of the major axis of IC 2497, and is therefore likely to be relatively unobscured.

In this scenario, we note that another possibility is that components C1 and C2 can be identified with luminous SNe or SNR. This applies in particular to C1, which may exhibit a high level of variability as indicated by its non-detection in the original e-VLBI observations (Józsa et al. 2009). However, we believe this to be very unlikely given the flat spectrum of C2 and the implied luminosities of the SNe, which would have to be in excess of 5.126×10^{21} Watts/Hz i.e. almost an order of magnitude brighter than the supernovae observed in Arp 220 (Parra et al. 2007). In addition, C1 appears to have a constant flux density over a time span of ~8 months, making a supernova interpretation extremely unlikely for this source.

If AGN activity is responsible for the ionisation of Hanny's Voorwerp, the AGN must have been radio quiet even at the time at which the ionising radiation was generated. At 1.4 GHz, assuming a typical magnetic field strength of $\sim 100\ \mu$G, the characteristic life time of the relativistic jet electrons is $\sim 9 \times 10^{6}$ years (e.g. Condon 1992), exceeding the light travel time to Hanny's Voorwerp by a factor of ~10. Hence, to judge whether the AGN at the centre of IC 2497 could have reached the bolometric or ionising luminosity sufficient to ionise Hanny's Voorwerp, one would need to search for radio-quiet AGN with similar ionisation structures at large distances. However, while targeted surveys of very luminous radio galaxies have previously discovered highly ionised gas (Tadhunter et al. 2002, 2007) at large distances (>10 kpc) from AGN, little is known about AGN with low radio luminosities such as that observed in IC 2497.

5. Summary

In conclusion, our results suggest that IC 2497 is an "active" galaxy in the broadest possible sense – it exhibits evidence of both a highly obscured AGN and nuclear star-forming activity in its central regions. There is also evidence (e.g. HI absorption, see Józsa et al. 2009) that our line-of-sight towards the nuclear regions of IC 2497 is obscured. Past interactions between IC 2497 and neighbouring galaxies have presumably triggered and fuelled both the AGN and enhanced star-forming activity observed, and are likely to be responsible for the creation of a huge reservoir of HI gas around the galaxy. We believe that Hanny's Voorwerp corresponds to that part of the debris trail that is illuminated by the AGN ionisation cone (and indeed the nuclear starburst).

Many AGN with weak radio sources exist but the presence of a large surrounding gas reservoir is most likely only present in interacting systems (such as LIRGs, which IC 2497 seems to be a prototype of). Given that galaxy interactions are relatively uncommon in the nearby universe, phenomena such as Hanny's Voorwerp while appearing extremely dramatic are expected to be quite rare. In the case of the Voorwerp, it seems that the location of this gas reservoir is also important, i.e., it must lie in the vicinity of the unobscured AGN illuminating cone.

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Table 2. Results of EVN 18 cm and MERLIN 6 and 18 cm observations, for both C1 and C2.

Component	Observation	α_{J2000}	δ_{J2000}	Size (mas × mas)	Physical Size (pc × pc)	PA (°)	S_{Peak} (mJy beam^{-1})	S_{Total} (mJy)
C1	EVN 18 cm	$09^h41^m04\overset{s}{.}089$	$+34°43'57''.78$	44.2 ± 0.7 × 31.4 ± 0.5	45.0 × 32.7	17 ± 2	0.876 ± 0.015	1.026 ± 0.028
	MERLIN 18 cm	$09^h41^m04\overset{s}{.}090$	$+34°43'57''.82$	222.5 ± 10.6 × 160.3 ± 7.6	231.4 × 166.7	35 ± 5	1.076 ± 0.035	2.464 ± 0.110
	MERLIN 6 cm	–	–	–	–	–	–	
C2	EVN 18 cm	$09^h41^m04\overset{s}{.}10$	$+34°43'58''.03$	58.1 ± 3.1 × 47.8 ± 2.6	60.4 × 49.7	141 ± 11	0.255 ± 0.014	0.609 ± 0.045
	MERLIN 18 cm	$09^h41^m04\overset{s}{.}10$	$+34°43'58''.02$	453.3 ± 17.8 × 282.4 ± 11.1	471.4 × 293.7	125 ± 3	1.430 ± 0.034	9.007 ± 0.2.43
	MERLIN 6 cm	$09^h41^m04\overset{s}{.}10$	$+34°43'58''.04$	139.6 ± 13.4 × 122.3 ± 11.7	145.2 × 127.2	6 ± 21	0.682 ± 0.065	1.120 ± 0.159