Mem. S.A.It. Vol. 93, 56

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Probing AGN feedback in the most luminous QSO at cosmic noon

M. Dadina[1], M. Cappi[1], E. Piconcelli[2], L. Zappacosta[2], S. Bianchi[3], C. Vignali[4], A. Bongiorno[2], M. Brusa[4], A. Bulgarelli[1], G. Cresci[5], A. De Rosa[6], A. De Rosa[1], G. Lanzuisi[1], F. La Franca[3], A. Marinucci[3], G. Matt[3], F. Nicastro[2], F. Tombesi[7], E. Torresi[1]

[1] Istituto Nazionale di Astrofisica – Osservatorio di astrofisica e scienza dello spazio, via Gobetti 93/3, I-40129, Bologna, Italy,e-mail: mauro_dadina@inaf.it
[2] Istituto Nazionale di Astrofisica – Osservatorio astronomico di Roma, via Frascati 33, I-00087, Monte Porzio Catone, Italy
[3] Universitá degli studi Roma Tre – Dipartimento di matematica e fisica, via della Vasca Navale 84, I-00146, Roma, Italy
[4] Universitá degli studi di Bologna – Dipartimento di fisica e astronomia, via Gobetti 93/2, I-40129, Bologna, Italy
[5] Istituto Nazionale di Astrofisica – Osservatorio astrofisico di Arcetri, largo Enrico Fermi 5, I-50125, Firenze, Italy
[6] Istituto Nazionale di Astrofisica – Istituto di astrofisica e planetologia spaziali, via del Fosso del Cavaliere 100, I-00133, Roma, Italy
[7] Universitá di Roma "Tor Vergata", Via Della Ricerca Scientifica 1, I-00133, Roma, Italy

Received: 13 January 2022; Accepted: 16 June 2022

Abstract. The formation and evolution of galaxies across cosmic times and their co-evolution with their central super-massive back holes are at forefront of the modern astrophysical research. Feedback mechanisms via AGN driven winds have been invoked in the last decade to explain how such structures may interact with each other. In our project we paved some possible ways to tackle this problem. We primarly focused on the study of AGN-driven outflows where it had to contribute the most, i.e. at the peak of accretion and star formation history (z∼2-3). We coupled to this approach also the study of nearby Seyfert galaxies so as to have a more complete view of the AGN-driven outflow phenomenon. Our results are in agreement with the basic idea that AGN-driven winds act as the mean for the feedback mechanism between the supermassive black-holes and their host galaxies at low but, more importantly, at high redshift.

Key words. Galaxies:active - galaxies:quasar - galaxies:Seyfert - X-ras: galaxies

1. Introduction

The discovery of the relations linking th properties of the bulges of the galaxies with the mass of their central super-massive black-holes (SMBHs) (Ferrarese & Merritt 2000) opened fundamental questions on how these structures evolve and interact between each-other across cosmic history. These relations were indicating the existence of some unexpected ingredients in the recipe for the formation and evolution of galaxies. Before this discovery, the presence of SMBHs was generally assumed to be almost completely irrelevant for the life of the host structures. It was supposed, in fact, that SMBHs act on their hosts only via their gravitational field that, in turn, is matched by the gravitational force of the stellar field at few pc from the SMBHs, i.e. at scales negligible when compared with the typical size of galaxies.

X-ray studies of AGN at low redshift ($z \lesssim 0.1$) highlighted that at least 40% of these objects show signatures of high velocity, mildly relativistic ($v \sim 0.1$-$0.4c$) outflows of ionized matter (Tombesi et al. (2010); Gofford et al. (2013)). They have been discovered in the X-ray band through their characteristic blueshifted iron resonant absorption lines above $\approx$7 keV. They are thought to arise at subparsec scales and are supposed to be able to expand in the surrounding interstellar medium (ISM). This discovery naturally offered a possible feedback mechanism able to link the fate of the "tiny" SMBHs and the bulge of the galaxies.

Theoretical models (e.g., King & Pounds 2015) describe the co-evolution of SMBHs and their host galaxy as mediated by fast accretion-disk winds, which could evolve into massive galaxy-scale outflows. These outflows may quench the host galaxy star formation by sweeping out all of its ISM. To be effective, the AGN feedback mechanism needs energetic inner winds (nominally with semi-relativistic velocities) with a mechanical power above the theoretical threshold of 0.5%–5%$L_{\rm bol}$ (e.g., Di Matteo et al. 2005; Hopkins & Elvis 2010). As introduced above, such X-ray winds, also known as ultra-fast outflows (UFOs; Tombesi et al. 2010, 2011, 2013; Gofford et al. 2013), being the most extreme winds known to date, are natural candidates to start this feedback mechanism. In a broader perspective, Gaspari & Sądowski (2017) showed that galaxy evolution might be regulated by the duty cycle of a multi-phase AGN feedback, with a feeding phase that is thought to be due to the so-called chaotic cold accretion (CCA, Gaspari et al. 2013). In this phase, cooled gas clumps and clouds "rain" toward the innermost regions of the AGN (e.g., Gaspari et al. 2018). While, as stated above, there is plenty of evidence about the outflowing phase, recent observations have started detecting also the feeding phase (e.g., Tremblay et al. 2016; Lakhchaura et al. 2018; Temi et al. 2018).

Furthermore, to be relevant for the AGN/galaxy co-evolution, AGN feedback must have been most effective at cosmic noon, i.e. at $z \sim 2$-3, when both AGN activity and galaxy star formation rates were at their peaks (Di Matteo et al. 2005). It is therefore fundamental to test the presence of UFOs and outflows also at these redshifts. However, the collection of good-quality data for high-z sources may be extremely challenging. It is therefore important to spot the best strategies to tackle this problem: for instance, a good strategy may arise having in mind that the power of the feedback mechanism increases with AGN luminosity (Zubovas & King 2012; Fiore et al. 2017). Being so, hyper-luminous objects provide a unique test-place for probing the SMBH-host galaxy interplay during the active phase.

The pieces of evidence presented above formed the scenario within which our project has been developed. It was originally focused mainly on the study of distant objects but it was naturally enriched and completed with the studies of some local Seyfert galaxies. Investigating low-z AGNs has a key role in testing wind launching mechanisms which are largely hampered by studies of distant QSOs.

2. Feedback in action in the high-z luminous QSOs

To overcom the problems related to the difficulties in collecting good-quality spectra for

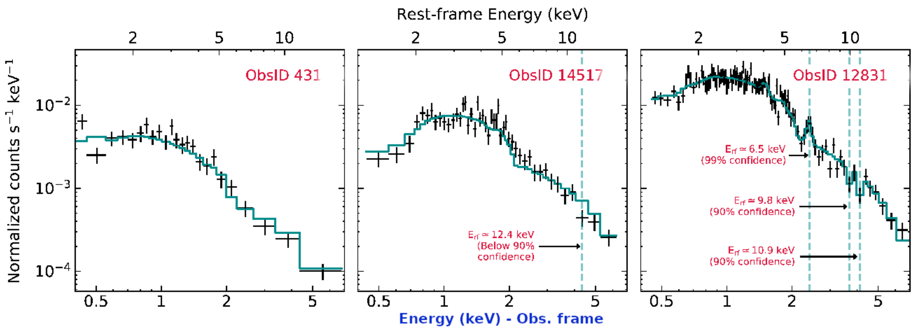

Fig. 1. Three examples of Chandra spectra of the Einstein Cross. The dashed lines indicate the energies of the emission and absorption lines found by adopting the blind-search method of Tombesi et al. (2010). Adapted from Bertola et al. (2020).

high-z objects, we adopted different strategies tailored to answer some specific questions: namely, we pointed to gravitationally lensed objects and to the most luminous QSOs.

2.1. *Inferring the UFO duty cycle using lensed QSOs: the case of the Einstein Cross*

Gravitational lensing offers, naturally, an additional lens to our telescopes. We started using this technique to obtain high-quality X-ray spectra of distant QSOs in 2016 (Dadina et al. 2016) and continued till current days. Moreover, some lensed QSOs have been extensively monitored to study micro-lensing phenomena. For the famous Einstein Cross, a radio-quiet QSO at z=1.695, we took advantage of the X-ray monitoring taken with Chandra to which we added long XMM-Newton exposures to have insights on the UFO duty cycle (this work is presented in Bertola et al, 2020).

In this way, Bertola et al. (2020) coupled the capabilities of XMM-Newton to obtain high-quality spectra with the large number of Chandra observations. This allowed the testing of the baseline model to be adopted in describing the X-ray continuum emission (in the ∼1-22 keV rest frame) and used in computing the significance of the measured absorption features due to the outflows. UFO signatures were common both in the Chandra (see Fig.1) and XMM-Newton data. The overall significance of the UFO was well above 4σ and, after a careful cleaning of the observations for which we were not able to collect at least 500 counts in the 0.1-7 keV band, we have been able to asses that the UFO duty cycle in this source was at least of 40% (see Fig. 2). This was the first time that a similar apporach was used for a distant QSO.

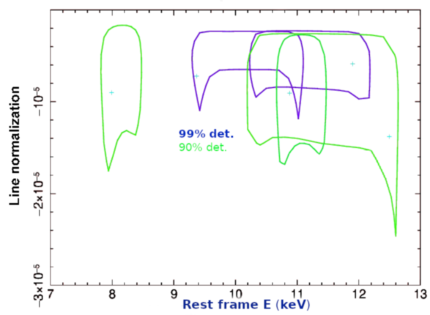

Fig. 2. 90% confidence contours (1.6σ) for the absorption lines (normalization vs. energy) measured with Chandra in the Einstein Cross in green, while in blue are those detected at more than 99% confidence level. Adapted from Bertola et al. (2020).

The recorded energies of the individually detected UFOs were found to be of the order of 10% of the bolometric luminosity, i.e. well above the threshold predicted by the models (0.5-5%, Di Matteo et al. 2005) to establish effective feedback. Moreover, the recorded lower limit on the duty cycle allowed to infer that the capability of establishing the link between the central SMBH and the host galaxy was not significantly affected by the duty cycle itself (Bertola et al. 2020).

2.2. Linking the properties of the outflows measured in optical to the AGN ionisation field in the high-z QSOs

If we move from the inner regions of AGN towards the typical distances of the BLR or more, we observed that the most luminous AGN are expected to exhibit the strongest and clear-cut manifestations of winds measured in optical and/or IR (Menci et al. 2008; Faucher-Giguère & Quataert 2012). Observationally speaking, the fastest and most energetic winds in these bands have been measured in hyper-luminous quasars (i.e. with a bolometric luminosity of $L_{bol} \gtrsim 10^{47}$ ergs^{-1}; Wu et al. 2011; Fiore et al. 2017; Vietri et al. 2018; Perrotta et al. 2019).

In order to fully characterise the multiplicity of winds, a program targeting the MIR-brightest WISE/SDSS quasars at redshift z≥1.5 (Bischetti et al. 2017) was started. Optical-to-UV data allowed to measure high velocity outflows at all scales, going from the detection of broad absorption lines (BAL) at circumnuclear scales (Bruni et al. 2019), to ionised galactic and circumgalactic scales outflows measured using optical lines (Bischetti et al. 2017).

In this context Zappacosta et al. (2020) investigated the possible connections between these winds and the coronal properties responsible of the high energy emission of the AGN, directly linking the outflows at large scales with the power of the AGN itself. A relation between $L_{2-10keV}$ (see fig. 3) and α_{ox} (indicating the optical to X-rays slope) with CIV was found, while there are no similar dependence using UV, MIR and bolometric luminosities.

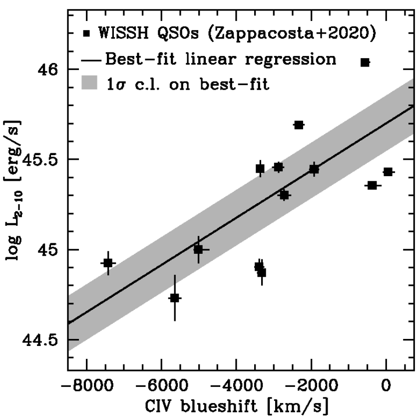

Fig. 3. $L_{2-10keV}$ vs CIV velocity for the WISSH QSO. Adapted from Zappacosta et al. (2020)

This result is in accordance with what expected in the theoretical scenarios for the launching mechanism of UFOs. In magneto hydrodynamic-driven wind scenarios (MHD, Fukumura et al. (2010)), in fact, we expect that the radiation fields do not drive the outflow velocity and, thus, the broadening of the CIV line. Nonetheless, the weaker radiation fields allow the non completely ionised CIV to survive closer to the accretion disk, i.e. where the outflow velocities are higher. In the radiation driven scenarios, the presence of failed winds able to shield the matter that is efficiently accelerated is mandatory (Proga et al. 2000). In this scenario we thus expect an anti correlation between the X-ray luminosity and the recorded velocity of the CIV, since the stronger the shielding, the stronger the reachable velocity.

3. A sharper look at the feedback mechanism in local AGN

The study of AGN in the nearby Universe allowed the measurement of UFOs in the X-ray spectra of Seyfert galaxies (Tombesi et al. 2010; Gofford et al. 2013). The high statistics collected with modern X-ray telescopes was fundamental. As such, the study of nearby AGN is still mandatory to characterise that mechanisms that may be acting also at high-z.

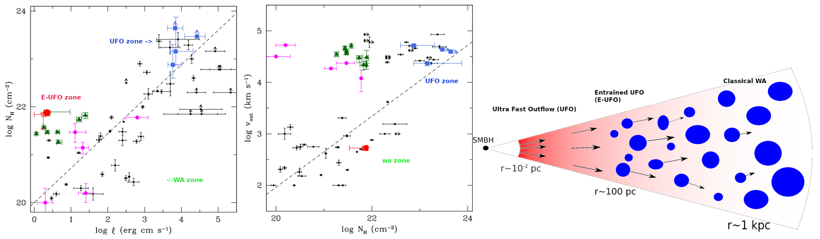

Fig. 4. Column density vs. ionisation parameter (left panel) and outflow velocity vs. column density plots (middle panel). Red stars are for WA, green triangles are for entrained-UFO (see right panel), blue squares for UFOs. Arrows represent limits on the column density, with the black dots and dashed line representing the linear fit from (Tombesi et al. 2013). In the right panel, the "picture" obtained from X-ray observations is shown. The UFO escapes with decreasing density ($\rho \propto r^{-2}$). At $r \simeq 100$ pc, the UFO interacts with the closest clumpy ambient entraining it. The clumps are then accelerated at velocities comparable with that of the UFO. Gas at larger scales is unaffected by the UFO retaining a significantly lower line-of-sight velocity. Adapted from Serafinelli et al. (2019)

For this reason, we studied also low-z objects. In particular, we tried to test at low-z the signatures that may link phenomena happening at different galactic scales moving from the very central regions of the galaxies, dominated by the SMBH, up to the entire galactic scales.

3.1. Linking UFOs with WAs: the case of PG1114+445

Tombesi et al. (2013) clearly demonstrated that in Seyferts classical warm absorbers (WA) and the newly discovered UFOs are somehow linked. This finding suggested that these two winds may be different phases of a single phenomenon expanding from the inner regions of the AGN towards the larger galactic scales. However, observational evidence for the interaction between the inner high-ionisation outflow and the ISM is still missing.

In this contest, PG 1114+445 was studied using all the available XMM-Newton and ASCA observation by Serafinelli et al. (2019). The X-ray spectrum of the source was found to display signatures of both classical WAs and UFOs. Along with these signatures, however, it was measured also the presence of another absorbing component with characteristics that are in the middle of these two kinds of absorbers. As sketched in figure 4 (left and middle panels), the new component was found to have the velocity typical of the UFOs, the ionisation state typical of the WA and column density somehow in between the two.

This has been interpreted as an indication of an intermediate zone in which the original UFO clashes with the clumpy regions at BLR distance forming blobs of still fast moving but cold gas (see the right panel of Fig. 4). According to this scenario, well supported by theoretical work (Zubovas & King 2012; King & Pounds 2015), the inner UFO drives into the surrounding medium, sweeping-up the gas outwards. In the aftermath of the shock, four regions are formed: i) the innermost region, containing the unshocked UFO, ii) the shocked inner wind, iii) the shock-induced swept-up interstellar gas, and (iv) the unaffected ambient medium. Overall, this picture is in good agreement with what predicted by models of self-regulating feedback mechanism for the evolution of galaxies (Gaspari & Sądowski 2017).

3.2. Linking X-ray and UV outflows: the case of NGC 3783

The observations of NGC 5548 taken in 2013 (Kaastra et al. 2014) revealed two related obscuring components that affected UV and X-rays. They had column densities of 10^{24} – 10^{25} cm^{-2} (X-ray covering factor of 0.86–0.30) and were able to significantly absorb the pri-

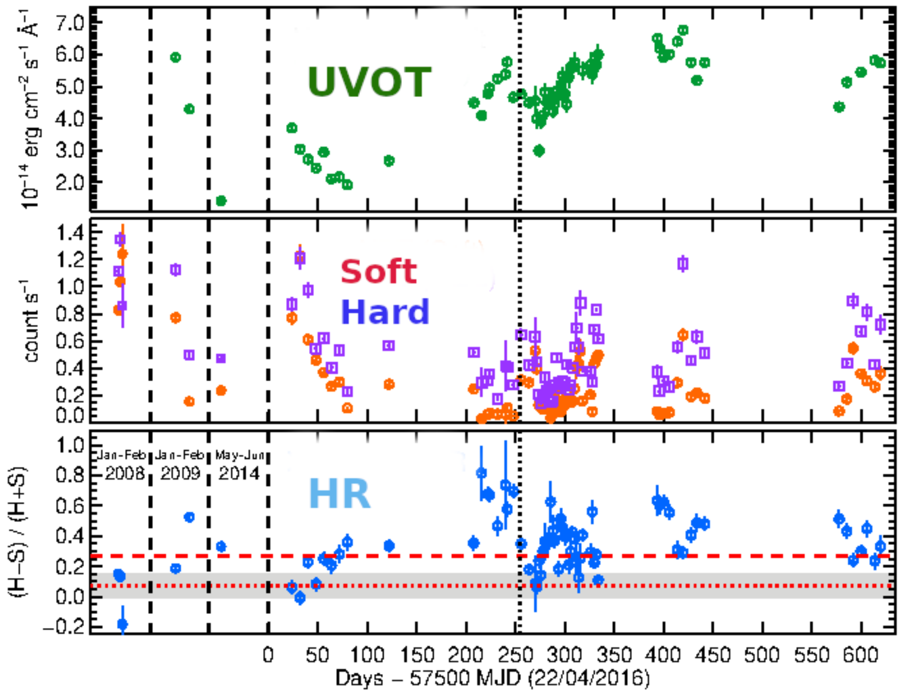

Fig. 5. Swift light curves of NGC 3783. Dotted black-vertical line is for 1 Jan. 2017. Two days averaged data are plotted. UVOT flux is in top panel; in middle panel are soft (0.3–1.5 keV) and hard (1.5–10 keV) count rates; in bottom panel there is the hardness ratio $R = (H - S)/(H + S)$. Dotted red line is for the average hardness ratio without obscuration; the gray area is for the typical variations due solely to photon index variability. The dashed red-horizontal line hardness is the triggering for strong obscuration events. Adapted from Kaastra et al. (2018).

mary emission of the central region of the source. Moreover, the UV absorber was fastly outflowing. This was a new finding that directly linked the X-ray obscuration with UV attenuation due to fast-moving gas.

This result has been at the base for a Swift monitoring program on some bright Seyfert galaxies. The goal was to catch them in "unexpected" obscured states adopting the X-ray hardness ratio against flux variability as a tracer of possible obscuration events on accretion disk scales. After the triggers, the sources were followed-up at all frequencies to study the evolution of the absorbers at different scales. The type 1 Seyfert NGC 3783 was catched in an X-ray obscured phase in December 2016 and this started the programmed deep multiwavelentgh campaign. One of the goals of this program was to estimate the duty cycles of these obscuration/outflows events. To this goal, Kaastra et al. (2018) collected all the possible X-ray observations of the target in the last twenty years. The obscuration events appeared to be frequent in NGC 3783 (see Fig. 5). About half of all Swift observations (i.e. ~50% duty cycle), considering also the archival ones, were affected by obscuration. Hints of obscuration events were found also in older ASCA and RXTE observations. Furthermore, the Chandra/HETG spectrometer data allowed us to track the obscuration events occurred in August and in December 2016. It

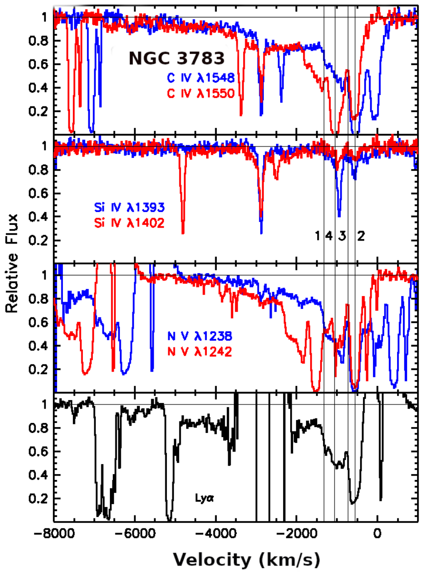

Fig. 6. Normalised spectra of the broad absorption features in NGC 3783 (2016-12-12). Adapted from Kriss et al. (2019).

was found that in August 2016 the obscurer had lower column density than that recorded four months later in December 2016. This was indicating variations on time scale smaller than the expected size of the torus (∼1 pc).

Moreover, the multiwavelentgh campaign allowed us to follow the evolution of the UV absorber by taking advantage of HST/COS coordinated observations (this work was presented in Kriss et al. 2019). The main result of this multi-wavelength campaign was the detection of a fast UV obscurer characterised by broad features (see Fig. 6). It displayed characteristics very similar to those discovered in NGC 5548 (Kaastra et al. 2014). The outflow had velocity going from 0 to a maximum value of −6200 km s^{-1}, and a maximum depth at −3000 km s^{-1}. The UV absorption was visible in Lyα, N v, Si iv, and C iv. In X-rays the measured column density was $N_H \sim 2.3 \times 10^{23}$ cm^{-2}. This, coupled with the UV ion column densities, yields an ionisation parameter of $\log \xi = 1.84^{+0.4}_{-0.2}$ erg cm s^{-1}, a value consistent with that of the highly ionised portions of the broad-line region.

Despite the very UV high-flux state, the intrinsic absorption lines have depths and ionisation states similar to the lowest flux states seen in the past. The deep troughs and low-ionisation states like C iii strongly indicate that the ionising UV must be shadowed by the soft X-ray obscurer, similarly to NGC 5548.

Overall, the emerging picture from the multiwavelentgh campaign suggested that the UV flux increases were probably driven by some sort of infall/accretion of matter coming from regions with sizes typical of the central portion of the BLR. The increased accretion from outside the plane of the accretion disk was able explain both the raised UV flux and the rise of the obscuration in X-rays.

4. Discussion and conclusions

One of the most relevant topic of modern astrophysics is the formation and evolution of galaxies over cosmic times and how they have been shaped by the existence of the SMBH that they host at their centre.

We tackled this topic by studying the AGN-driven feedback mechanisms using multiwavelength data in both low-z and high-z objects. This allowed us to test in detail the interaction of AGN driven fast moving outflows (the UFOs) with the circumnuclear matter bot at sub-parsec and parsec scales. This kind of studies is possible at low-z where the current telescopes allow collecting good enough data. The results obtained on PG1114+445 and NGC 3783 indicate that the inner regions of AGN are dominated by fast moving matter as predicted by theoretical models (King & Pounds 2015).

This picture is somehow more extreme at high-z. The work on the Einstein Cross clearly indicates that UFOs are most probably typical at the peak of the star formation history and that only the paucity of photons often hamper their detection and full characterisation. In this respect, it is important to stress that similar studies using gravitational lenses are drawing a picture in which the detection rate of UFOs is remarkably high (Chartas et al. 2021). Moreover, the discovery of the relations found for WISSH QSOs are perfcetly in agreement with what predicetd by the launching mechanisms of UFOs. Thus adding another piece of evidence to the picture for which AGN driven winds are responsible for the SMBH-host galaxy feedeback.

Among the obtained results (that count at least 29 refereed papers, for example) we would like to stress some other important issues: the works presented here are perfectly nested in the international research scenario. One of the most striking evidences for this is that we are involved in the development of future observational facilities such as Athena and/or in international collaborations in this field. More importantly, however, this program, generated a strong collaboration among the involved researchers that naturally evolved onto large observational projects. One of them, the SUBWAYS program (Brusa et al. 2019), was somehow meant to fill the gap in redshift between the two extreme touched in this program. This expertise has been awarded, moreover, with large programs with all the existing facilities (starting from XMM-Newton, to NuSTAR, MUSE, ALMA) available to date.

Acknowledgements. The authors acknowledge financial support from the Italian Space Agency under the agreement ASI-INAF n.2017-14-H.O.

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