Inner structure and global kinematics: Arp 220 revisited

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Abstract.

With an infrared luminosity of $10^{12.2} L_\odot$, Arp 220 is one of the prototypical Ultraluminous Infrared Galaxies. It’s high IR luminosity, the presence of tidal tails detected in the optical, the double infrared and radio nuclei, and the perturbed optical ionized gas kinematics measured at large scales support the fact that Arp 220 is the late phase of an on-going merger. This, along with the most accepted evolutionary theories for ULIRGs, indicate that Arp 220 may evolve into an intermediate mass elliptical galaxy. Nonetheless, there are several questions that still remain open, such as the exact location and number of nuclei, their relation with the X-ray emission, and the kinematic behavior of the galaxy at different scales. Here we give an overview of what we know about Arp 220 up to date, regarding the NIR and radio regime, and report on new insights in kinematics and the structure on larger spatial scales of the merger making use of IRAM PdBI observations.

1. Introduction

Ultraluminous IR galaxies (ULIRGs) are a galaxy class characterized for having an IR luminosity of $10^{12} L_\odot \leq L_{bol} \sim L_{IR} [8-1000 \mu m] \leq 10^{13} L_\odot$. They are thought to be powered by either a strong nuclear starburst ([6]), a heavily obscured active galactic nucleus (AGN, [13]) or a mixture of the two. Whatever the power source may be, a large molecular gas concentration in the central kiloparsecs is needed in order to be sustained (see e.g. [12]). Various scenarios linking the evolution of ULIRGs to QSOs have also been suggested (e.g. [12]).

At a distance of $D_L = 78$ Mpc ($\Omega_M = 0.7, \Omega_\Lambda = 0.3$, and $H_0 = 70$ km s$^{-1}$ Mpc$^{-1}$) and with a luminosity of $L = 1.4 \times 10^{12} L_\odot$ ([17]) Arp 220 is a prototype ULIRG. Extended tidal tails, apparent in the optical ([1]), as well as the double nuclei revealed in the radio and the near-infrared regime (e.g. [8]), indicate that the galaxy is in the final stage of merger. The evolutionary scenarios linking ULIRGs to QSOs allow the possibility that a weak, but growing, AGN ([18]) may lie at the center of Arp 220. Competing theories claim a pure nuclear starburst contribution, contributions from hot cores (see e.g. Martin-Pintado, this conference) or a mixture of AGN and starburst to explain the high IR luminosity ([11]), arguing with the rather high star formation rate of $340 M_\odot yr^{-1}$ ([2]). Fe K\alpha emission at 6.3 keV was detected at slightly more than $3\sigma$ significance, although there is no angular resolution for resolving the galaxy. This may also indicate the presence of an AGN deeply embedded by dust. The overall gas content
was estimated to be $\sim 9 \times 10^9 M_\odot$ ([16]). The fact that [OIII]5007, which is a good AGN tracer but also sensitive to star formation, is not detected in the optical supports the extremely high extinction (see e.g. [3]). Optical observations reveal that the galaxy is clearly crossed by a dust lane spreading from NE to SW (see Fig.1a). High resolution radio and near-infrared imaging revealed a complex nuclear structure: The core of Arp 220 appears to have (at least) two different nuclei (or nuclear regions). They are identified as Western and Eastern nuclei, separated by about 0.4 kpc (at this redshift 0.018 kpc correspond to about 1’). The Eastern nucleus is divided into two components: North-East and South-East. CO (1-0) observations revealed an underlying rotating kpc-sized molecular gas disk ([14]). The presence of compact sources identified as SN (at 13, 6, and 3.6 cm) was detected by [9]. A comparison between CO and near-IR data shows consistency in the number of sources, but not in their relative position. This may be due to: (1) the fact that different wavelengths trace different gas phases, or (2) differential extinction. Following it’s position in the proposed evolutionary scenarios (see earlier in the text), Arp 220 can provide the link between ULIRGs and elliptical galaxies. Furthermore it can be considered as a benchmark in understanding these complex objects in detail. Arp 220
may also turn out to be something useful to explain the rotating-like structures detected in high-redshift ULIRGs (see [7]). Studying Arp 220 and other ULIRGs in the local universe, in this high resolution configurations may enable us to draw conclusions for radio detected galaxies at high redshifts, which we cannot study in this great detail, yet.

2. Observations and data reduction
The HST/WFPC2 F814W archive image was reduced 'on the fly' using the best reference files at the moment of retrieval. In this article we only show this image as a reference. Details on the NICMOS data reduction can be found in [15]. CO 1 and 3 mm line and continuum observations with different spatial scales and resolutions were carried out with the IRAM Plateau de Bure interferometer (PdBI) in different configurations during the years 1994, 1996, 1997 and 2006, respectively. Depending on the observational setups and the data reduction, the synthesized beam sizes range from $0.30'' \times 0.30''$ to $4.99'' \times 3.50''$. The resulting CO data cubes were analyzed with the MAPPING package of IRAM's GILDAS\(^1\) software.

3. Unveiling the central kiloparsecs
With CO PdBI observations and archival HST images, we can analyze the dust distribution and the distribution of the star forming regions, disentangle the position of the true nuclei, study the kinematics at different scales, and draw an interesting picture of the central arcseconds of Arp 220.

3.1. Arp 220 West
Arp 220 West is the brightest source in the near-IR (Fig. 1b), in CO (2-1) (Fig. 1c), CO (1-0) and in the 1.3 mm continuum. The 2.2 \(\mu m/1.1 \mu m\) color map (Fig. 1d) however reveals that the peak of the dust distribution is not associated with this nucleus. The CO (2-1) spectra show deep absorption (Fig. 1c) that can be explained by the presence of foreground material. The complexion of the CO emission can be modeled best by a ring or disk around a compact dust core. Size, luminosity and rotation pattern observed in CO (2-1) support the presence of a black hole ([5]).

![Figure 2. Left: East-West CO (2-1) position-velocity cut through Arp 220 from CO-NE to CO-SW, with the 1.3mm continuum subtracted, considering CO-SE as the rotating center and a radius of about 0.3''. Middle: CO (2-1) velocity field of the central 3'' of Arp 220, with a beam of 0.30''. Right: CO (2-1) velocity dispersion distribution, showing two prominent peaks at the positions of CO-West and CO-SE and a possibly fainter third one towards CO-SW.](http://www.iram.fr/IRAMFR/GILDAS)
3.2. Arp 220 East

The Eastern nucleus, which is veiled in the optical wavelengths, can be resolved into a NE and a SE part. Arp 220 East is the secondary source in the near-IR, CO (2 - 1) and CO (1 - 0). The near-IR color map (Fig. 1d) points at CO-SE as the peak of the dust distribution. Using H - K and a standard extinction law ([10]), A_V for the SE and NE nuclei are 24 and 18 mag, respectively. In addition, the CO (2 - 1) spectra show the deepest absorption in this region (Fig. 1f). Along with the velocity dispersion distribution (Fig. 2c), peaking on the position of CO-SE rather than on CO-NE, this seems to point out CO-SE as the 'real', but deeply embedded and/or highly dust obscured, nucleus of Arp 220 East. With the information provided by the emission width peak being located on CO-SE and the velocity field it is possible to assert the presence of rotating material around the SE nucleus. A possible third nucleus, CO-SW, is clearly identified in the near-IR, in CO (2 - 1) (Fig. 1c) and CO (1 - 0), although it is not detected in the 1.3 mm continuum (see Fig. 2, [5]). In fact it approximately coincides with the secondary peak of the 3-7 keV image. The extinction derived from the near-IR is A_V = 17 mag. The structure of the line width map shows a further mass peak, towards CO-SW. This enhancement could be produced by a mass concentration, but it can also act as a tracer for turbulent motions due to the merger process. Although the true nature of CO-SW is still unclear, it could possibly host an additional very faint nucleus, a huge star forming region, or a remnant of the merging process from one of the colliding galaxies.

4. The different kinematic scales in Arp 220

All velocity fields derived from the nuclear regions show rotation-like patterns at different scales (see Fig. s 2a, 3). Only in the outer regions, observed at optical wavelengths, the velocity pattern is disordered and apparently dominated by the merger. In the inner 2 kpc there are influences from the outflows coming from the dust-enshrouded nucleus. A CO (2 - 1) position-velocity diagram obtained for Arp 220 West shows strong variation from negative to positive velocities over the central 0.2" ([5]). For Arp 220 East (Fig. 2a) it also shows a variation from negative to positive velocities, considering CO-SE as the rotating center and a radius of about 0.3". The rotational motion found in Arp 220 East corresponds to the overall rotation of the underlying molecular disk discovered by [14] (see also Fig. 3). The two dimensional emission line width peaks in the SE nucleus (with about the same value as in the West), and based on the velocity field it is possible to assert that there is material rotating around it. On the position of CO-SW the velocity field shows a rotation pattern centered in this region and the pv-diagram shows a depression that may be interpreted as rotation, too.

Figure 3. Velocity field of the high-resolution CO (1 - 0) emission of the central 6° of Arp 220, with a beam of 0.60".
5. The large scale picture

The internal structure of Arp 220 has been studied extensively over the years. Nonetheless, little effort has been dedicated to study the more external regions although there are indications for activity in these regions, too. The elliptical-like envelope may be consistent with: (1) a late merger phase, and (2) the elliptical-through-merger scenario. The fact that near-IR light profiles follow an $r^{-1/4}$ law ([19]) corroborates the last statement. Until today it is not clear yet what happens in the outer regions of this object. For the first time we try to detect and study the molecular gas outside the central 3". There are indications, in the CO (1-0) low resolution maps, for emission about 10" towards the south, as well as to the north and to the west of the nuclei (Fig. 4). The preliminary velocity field of the large scale structure coincides fairly well with the IFU optical data from [3]. A recent re-analysis of the data used in [4] makes us confident, that the detection is real.

![Figure 4](image_url)

Figure 4. Integrated intensity map of CO (1-0) emission in Arp 220 integrated over 730 km s$^{-1}$ with a beam of 1.57" × 1.11".

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