Tidal Dwarf Galaxies

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1. Introduction

The birth and evolution of galaxies are dramatically affected by environmental effects. Interactions with the intergalactic medium and collisions with companions cause major perturbations in the morphology and content of galaxies. As a result, late-type spirals may evolve into early-type spirals or even ellipticals. In "bottom-top" models, larger structures form from the agglomeration of smaller entities, and small galaxies would be swallowed by giant galaxies.

A more exotic – and somehow reversed – way of forming galaxies was put forward by Schweizer (1978) and more recently by Mirabel et al. (1992), who found evidence for the genesis of a dwarf galaxy out of material removed from the interacting system NGC 4038/39. The idea that parent galaxies could give birth to dwarf galaxies goes back to the sixties, when the first photographic catalogues of extragalactic "perturbed" objects were published (Vorontsov-Velyaminov, 1959; Arp, 1966). These systems show numerous luminous clumps, attached to giant galaxies by jet-like thin filaments. At that time, some authors (Ambartsumian, 1961; Arp, 1972), invoking nuclear processes similar to those responsible for radio jets, claimed that giant galaxies could "eject" in the intergalactic medium a substantial part of their stellar mass. The crucial role of interactions and gravity was better understood when numerical simulations (e.g. Toomre & Toomre, 1972) demonstrated how tidal forces shape the stellar structures of interacting systems, creating tails, bridges and shells. Recent studies, based on optical and HI observations, have shown that debris of collisions actually form a class of "recycled" or "second-generation" galaxies that has several properties in common with classical dwarf galaxies: blue compact (BCDGs) or irregulars (dIrrs). Because they are mostly found in tidal tails, they are now commonly referred as "tidal dwarf galaxies" (hereafter TDGs).

We report here the results of a multi-wavelength campaign on tidal dwarfs carried out at La Silla, with several telescopes and instruments. Our aim was to identify and characterise objects of tidal origin in the environment of nearby interacting systems.

Figure 1: A tidal dwarf in the prototype interacting system NGC 4038/39 (The Antennae): This classic system is composed of two overlapping, distorted, late-type spiral disks. The two nuclei seen in the near-infrared K' image (inset) are separated by 15 kpc. More than 60% of the HI (green contours) is distributed along the tails. The object at the tip of the southern antenna shows a chain of HII regions, embedded in a low-surface brightness envelope (Mirabel et al., 1992). Optical image from the Digital Sky Survey; infrared image taken with IRAC2; HI contours from Hibbard et al. (1997). The field of view is 17.7′ × 19.5′.

2. Observations

The optical observations were carried out using EFOSC1 on the 3.6-m and EMMI on the NTT, during several runs between 1992 and 1995. Deep large-field BVR images were first taken. We identified in tidal features associated with colliding galaxies blue condensations, and obtained spectra of each of them using multi-object spectroscopy techniques. For each field, one mask containing 20–30 slits had been punched. We used the low-resolution grism #3 in the RILD mode of EMMI. Despite several false alarms – background galaxies with discrepant redshifts – we found in almost all systems between one and ten tidal dwarfs, exhibiting recent star formation revealed by the presence of ionised gas. In order to study the stellar populations of tidal dwarfs, and their star-formation history, we started in February 1996 a near-infrared imaging programme. JHK' images were taken with IRAC2B on the ESO/MPI 2.2-m. Because of the relatively small field of view offered by this camera (2′ with the lens LC), compared to the typical size of our objects (10′), we had to mosaic the field and therefore could map only few systems. In that respect, much observing time will be gained using SOFI, the next-generation

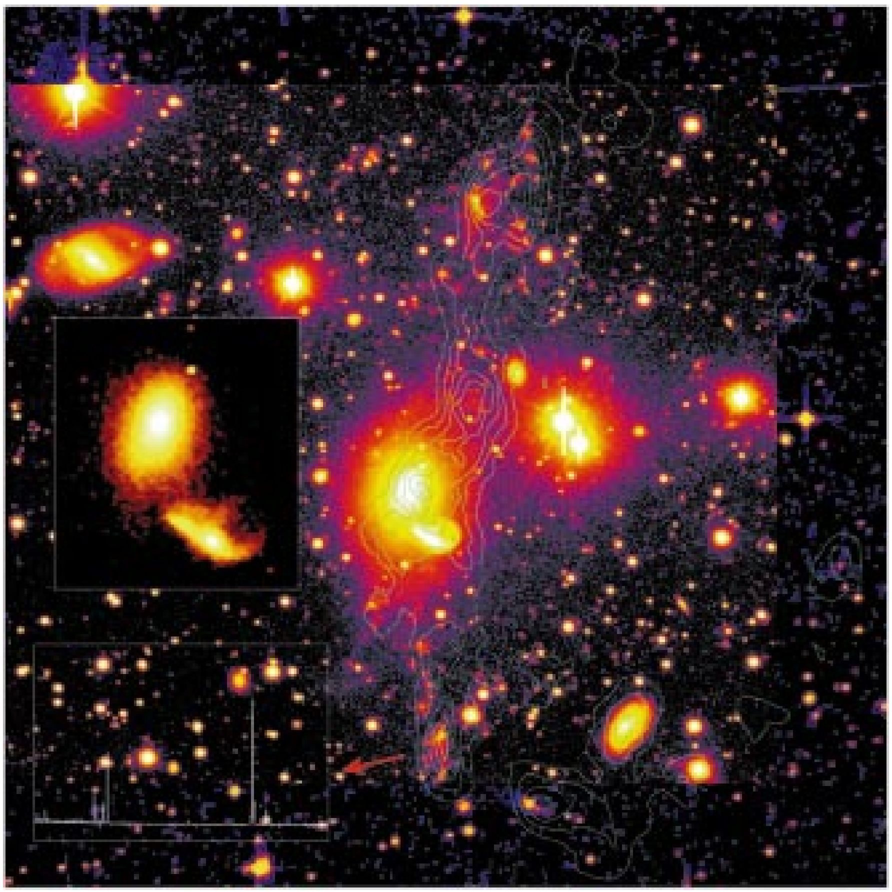

Figure 2: Very young tidal dwarfs in NGC 5291, an S0 with a huge HI ring: This lenticular galaxy is associated with a massive HI ring (green contours), perhaps formed after a high-speed collision with the disturbed object near the S0 (The "Seashell"). The inset shows a near-infrared K' image of the colliding galaxies. Associated to the HI clumps in the ring are found very blue ($B-V < 0.3$) optical counterparts. Multi-object spectroscopy reveals that they host active star-forming regions (see HII-like spectrum at the bottom-left). Optical R image and spectrum obtained with EMMI, K' image with IRAC2; HI from Malphrus et al. (1995). The field of view is $9.2' \times 8.7'$.

ESO infrared camera, to be installed next year on the NTT. In one of its modes, SOFI will offer a 5′ field. Our IRAC2 observations have already shown that low-surface brightness tidal tails can be detected up to 2.2 µm even on a 2.2-m telescope.

This optical and infrared work was complemented by radio observations of the atomic hydrogen, carried out with the Very Large Array interferometer, either by our group or other researchers, who kindly provided us with the datacubes.

As test cases, we present in Figures 1–4 different examples of interactions: spiral-spiral collisions (NGC 4038/39 or "The Antennae", Fig. 1; NGC 2992/3, Fig. 4) and spiral-elliptical encounters (NGC 5291, Fig. 2; Arp 105, "The guitar galaxy", Fig. 3). On the optical NTT images, long tidal tails are clearly seen emanating from the parent galaxies. At their tip, at a distance of 50–100 kpc from the nuclei, we found small irregular objects. Their absolute magnitude is in the range of dwarf galaxies. They host blue compact clumps that we identified with star-forming regions. Their spectra show emission lines, typical of HII regions, ionised by massive OB stars younger than 10 Myrs. Given the time scale for the formation of clumps in tidal tails – typically 1 Gyr (Barnes & Hernquist, 1992) – the young stars at the end of the antennae must have been born *in situ*. In Figures 1–3, the contours of the HI column density are superimposed in green on the CCD images. It is striking on these images that the central regions of the parent galaxies contain little atomic gas, whereas the optical tails, and especially the tidal dwarfs, are associated with HI clouds as massive as 5×10^9 $M_\odot$. Such a gas distribution in interacting

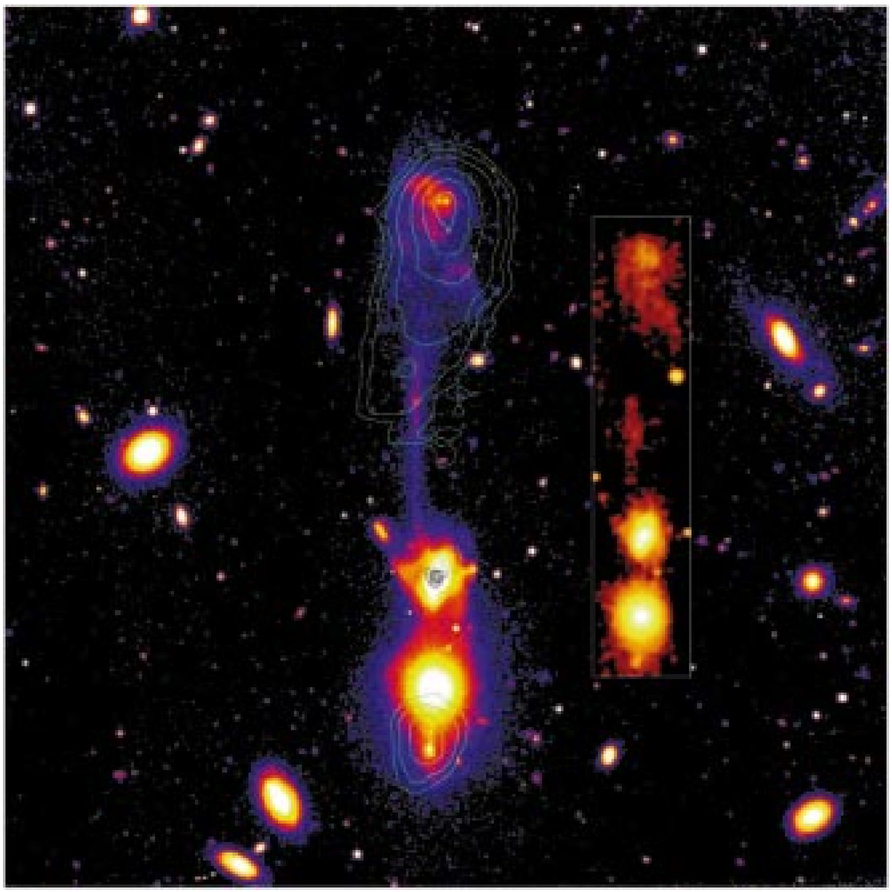

Figure 3: A gravitationally bound tidal dwarf in the spiral-elliptical colliding system Arp 105: The diffuse object at the end of the 70-kpc long tidal tail escaping from the spiral is as luminous as the LMC/SMC. The 6×10^9 $M_\odot$ HI cloud associated with the tidal galaxy shows evidence of rotation. Another tidal dwarf is seen south of the elliptical. Note in that system the extreme spatial segregation between the atomic (green contours) and molecular gas (black contours). V band image obtained with EMMI, near-infrared J-band image (inset) with IRAC2; HI and CO from Duc et al. (1997). The field of view is $7.5' \times 7.5'$.

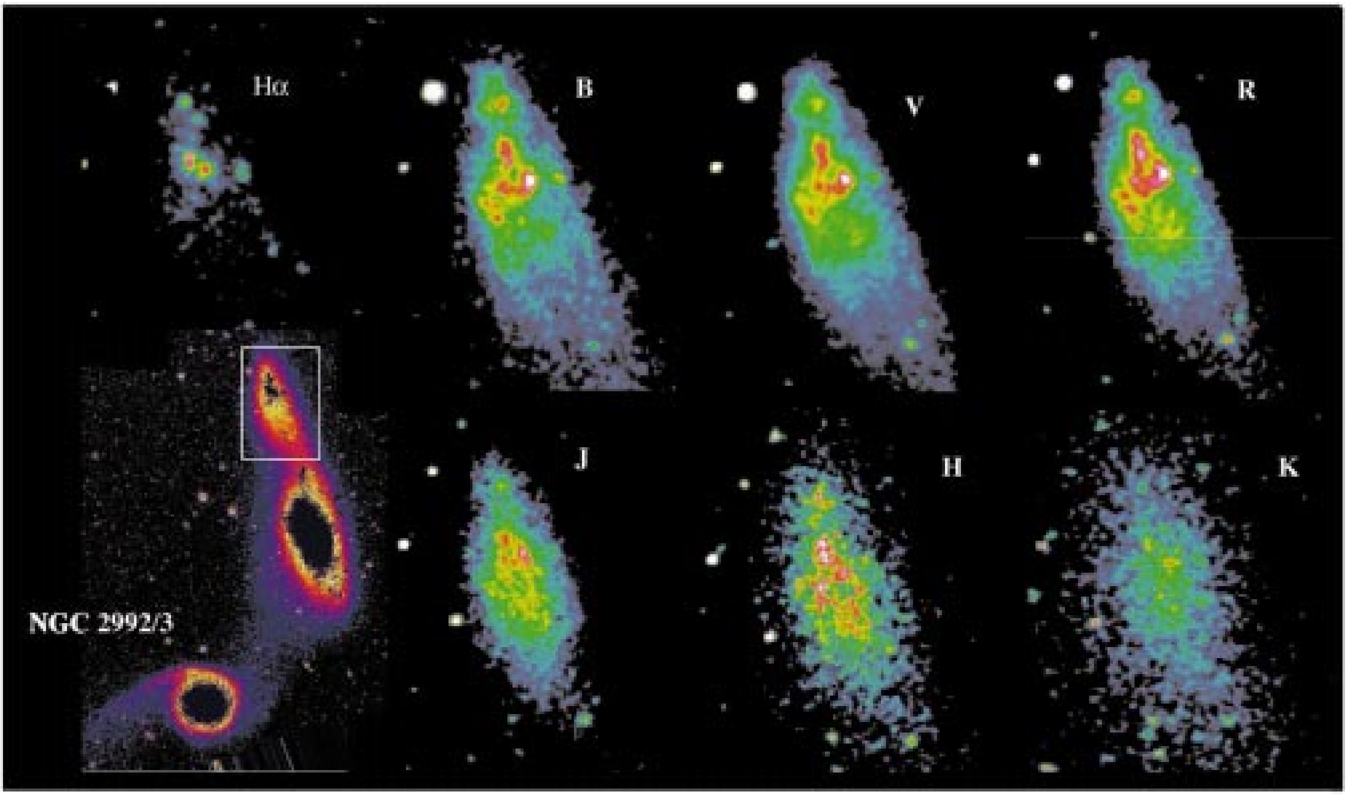

Figure 4: A tidal dwarf in the tail of the spiral-spiral colliding system NGC 2992/3. This figure displays multi-band images of the northern tail of NGC 2992. The spectral energy distribution of the tidal dwarf is dominated by old stars, formed in the disk of the parent galaxy. Optical images obtained with EMMI, near-infrared images with IRAC2.

systems seems to be quite general (Hibbard & van Gorkom, 1996). Above a critical HI column density between 5×10^{20} cm^{-2} and 10^{21} cm^{-2}, we detect emission lines from gas ionised by massive stars.

3. Properties of Tidal Dwarf Galaxies

3.1 Stellar populations

Tidal dwarf galaxies are made of two main stellar components: young stars recently formed by collapse of expelled HI clouds, and an older stellar population, at least 1 Gyr old, which was pulled out from the disk of the parent galaxies. Aperture photometry measurements, coupled with evolutionary synthesis models, allowed us to derive the proportion and age of both populations. Figure 5 displays on a V-K vs B-V diagram the near-infrared and optical colours of TDGs and for comparisons photometric measurements for the outer regions of their parent galaxies. Although our data-base is still limited, this figure shows that there may be a diversity of tidal dwarfs. On one hand, we find TDGs dominated by old stars with integrated colours comparable to those of the outer disk of their parent galaxies (e.g. NGC 2992, Fig. 4). In this type of objects, the recent star-formation episodes did not affect much the overall stellar population, and the K-band flux traces red giants. On the other hand, we find TDGs having extremely blue colours (B-V $<$ 0.3; V-K $\sim$ 2) (e.g., NGC 5291, Fig. 2), with no compelling evidence for the presence of an underlying old stellar population. In this case, the K light comes mainly from red supergiants younger than 20 Myrs.

Therefore, some tidal dwarf galaxies in the nearby Universe are instances of genuine young galaxies that are forming their first generation of stars. This class of objects are usually sought in the early distant Universe, where detailed studies are difficult. It has been debated whether another class of galaxies, the blue compact dwarf galaxies (BCDGs), are also of recent origin. A sample of them has been added in Figure 5. Although the B-V colour of BCDGs and TDGs are similar, their V-K index seems to differ quite significantly. This could be explained by a metallicity effect. The V-K colour of a starburst depends strongly on the metallicity during the first 20 Myrs (Cerviño & Mas-Hesse, 1994). Classical BCDGs born in primordial HI clouds are metal deficient objects (commonly $Z < Z_\odot/10$), whereas TDGs are formed from

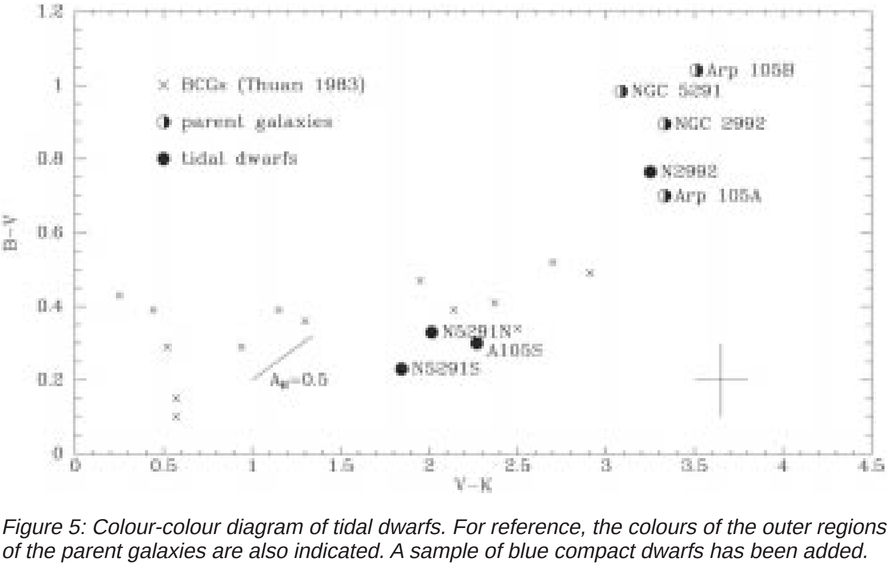

Figure 5: Colour-colour diagram of tidal dwarfs. For reference, the colours of the outer regions of the parent galaxies are also indicated. A sample of blue compact dwarfs has been added.

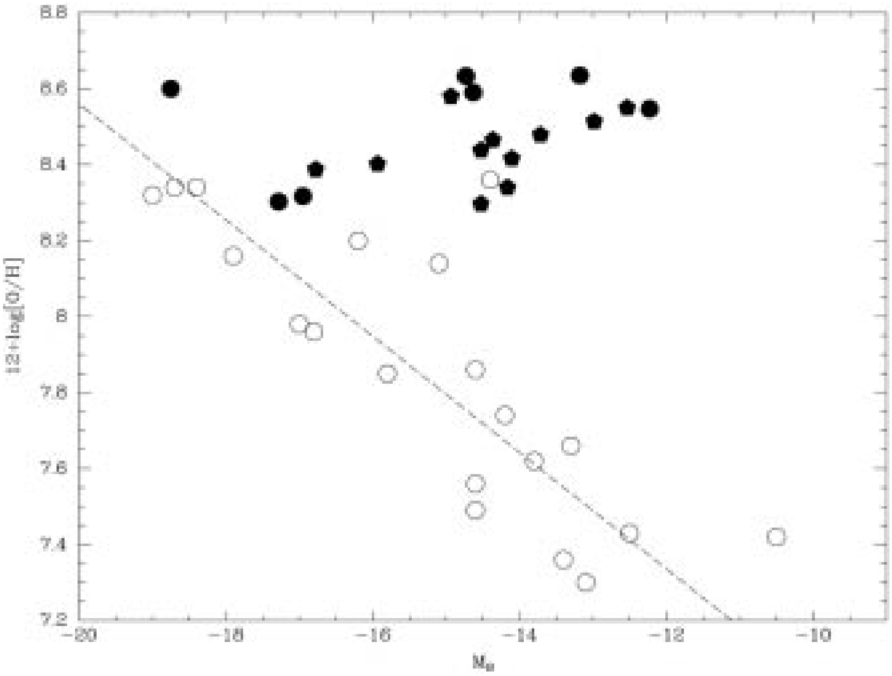

Figure 6: Oxygen abundance vs absolute blue magnitude for our sample of tidal dwarfs (black points) and a sample of isolated dwarf irregular galaxies (open points; from Skillman et al., 1989).

recycled material – material which has been pre-enriched in the disk of their parent galaxies – and therefore should be more metal-rich. This is consistent with the relatively high oxygen abundances we estimated in the HII regions of TDGs: $Z_\odot/3$ on average, a value typical of the outer regions of spirals. A clear result from our spectral analysis is that tidal dwarf galaxies do not follow the classical correlation found for field dwarf and giant galaxies between luminosity (hence mass) and metallicity, as shown in Figure 6.

3.2 Dynamics

Radio observations of the 21-cm HI line can be used to derive the dynamics of the gas. Unfortunately, most tidal dwarfs found so far have small angular sizes compared to the radio synthesised beams of the interferometers and the detailed study of the line profiles is difficult. However, there is a tidal dwarf where has been found evidence for rotation (Duc et al., 1997a) suggesting some sort of dynamical independence. Because of the low surface brightness of TDGs, the knowledge of the stellar dynamics derived from absorption lines is still beyond the scope of the current instrumentation. However, we expect that an IR spectrometer like ISAAC, to be installed on the first unit of the ESO VLT, will achieve the required sensitivity. An obvious by-product of these kinematical studies will be the determination of the TDG dark-matter content, which is expected to be low in the numerical simulations by Barnes & Hernquist (1992).

4. Formation of Tidal Dwarf Galaxies

It is known that interactions trigger star formation (e.g. Kennicutt et al., 1987). However, until the discovery of the tidal dwarf galaxies, this phenomenon had been observed mostly in the central regions of merging galaxies. For instance, almost all ultraluminous infrared galaxies, which host violent nuclear starbursts, are close interacting galaxies (see review by Sanders & Mirabel, 1996 and Duc et al., 1997b).

How can collisions induce star-forming episodes at distances as high as 100 kpc from the galactic nuclei? The related mechanism involves mass transfers mostly driven by gravitational forces. Following the interaction, a fraction of the atomic hydrogen loses its angular momentum, sinks into the central regions where it may be transformed into molecular gas, fuelling a nuclear starburst or an AGN. Another part of the HI, initially situated in the outer regions of the disk and therefore less gravitationally bound to the galaxy, is stretched and tidally pulled out into the intergalactic medium, supplying the material that leads to the formation of tidal dwarf galaxies.

The relative proportions of old and young stars that we derive from our observations are an important constraint for the models of TDG formation. Models based on numerical simulations of colliding systems favour two mechanisms: a local dynamical instability in the old stellar populations of tidal tails, followed by accretion of gas (Barnes & Hernquist, 1992) or collapse of a supermassive cloud triggering precipitous star-formation activity (Elmegreen et al., 1993). The two scenarios predict a different fraction of old to new stars.

5. The Fate of Tidal Dwarf Galaxies

Do tidal dwarf galaxies contribute significantly to the overall population of dwarf galaxies? The answer to this fundamental question relies, from a theoretical point of view, on the knowledge of two critical parameters: (1) the frequency of galactic interactions, believed to be increased with redshift; (2) the survival time of tidal dwarfs. The latter is limited by the hostile environment of TDGs, in the vicinity of giant parent galaxies. They may fall back on their progenitors, as pointed out by Hibbard & Mihos (1995), or be tidally disrupted. In this respect, the indication that some TDGs are gravitationally bound (Duc et al., 1997a; Hibbard et al., 1997) suggests the possibility of a longer life expectancy.

From an observational point of view, the census of TDGs is not an easy task. TDGs should obviously be searched in the environment of interacting galaxies. Optical images taken recently with SUSI during the Big-Bang period of the NTT disclose tens of new tidal dwarf candidates around several colliding galaxies. Hunsberger et al. (1996) claim from the analysis of photometric data that half of the dwarf galaxies in an Hickson compact group could be of tidal origin. However, one should note that once the stellar/gaseous bridge between the parent and child galaxies has dissipated, it is difficult to re-establish a link between the two. Our study has shown that a good genetic fingerprint of TDGs is their high metallicity. In this respect, several studies have put forward trends for dwarf galaxies in groups or clusters to be more metallic than field dwarfs (Bothun et al., 1985; Vilchez, 1995). Since the collision rate is enhanced in denser environments, it is tempting to argue that a significant fraction of dwarfs in clusters could be recycled objects. We are currently carrying out at La Silla an imaging and spectroscopy survey to quantify this effect in the Hydra cluster. A bimodal star-formation history is also a strong signature for tidal dwarfs. Evolutionary Synthesis Models simulating a burst of star formation on top of the underlying component of old galaxies reproduce well the TDG star-formation history and will give constraints for their future evolution.

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The Activity of Comet 29P/Schwassmann-Wachmann 1 Monitored Through the CO J(2–1) Emission Line at 230 GHz

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CO J(2–1) emission from comet 29P/Schwassmann-Wachmann 1 at 230 GHz was observed on 16 occasions with the 15-m SEST antenna from 4 December 1996 until 2 January 1997. A clear signal was detected in all daily averaged spectra, and day-to-day nuclear output variations by a factor ~ 2 were observed. Whatever the position of the telescope main beam in the coma, the line position and shape showed remarkably stable characteristics, which justified to combine the spectra to produce line profiles with S/N greatly enhanced over previous observations of the same kind. While most of the outgassing occurs from the sunlit side of the nucleus, night-side emission is also present. The shape of the lines near zero velocities in offset spectra cannot yet be uniquely interpreted. Whatever the ultimate model proposed to explain these observations, important implications for our understanding of how CO molecules are stored in the nucleus and later released into the coma may be derived from this data set.

Comet 29P/Schwassmann-Wachmann 1 (hereafter designated as SW1) was long the only object of proven cometary nature found to orbit the Sun entirely outside the orbit of Jupiter, at an average distance of ~ 6 AU. Rickman speculated in 1985 that Chiron, an object of apparently cometary nature and giant size, only physically observable with large-size telescopes, could be one of the largest members of an unseen population of comets orbiting the Sun between the orbits of Jupiter and Neptune[1]. In recent years, an ever-growing number of solar-system objects have been discovered that are also constantly situated far from the Sun. They form the now called Centaur and Kuiper Belt (KB) families, two groups of bodies that circulate between the orbits of Jupiter and Neptune and on average beyond that of Neptune, respectively. From a dynamical point of view, the Centaurs may be escapees from the Kuiper Belt. While the true nature of these newly discovered objects still remains to be unveiled, the current thinking is that they are the largest members of a vast reservoir of potential comets proposed by Fernandez[2] in 1980 to provide an important additional source of short-period comets beside the Oort cloud. The Centaur and KB populations should contain numerous small comets that are not observable with today's instruments. It is currently impossible to state whether SW1 was captured from the Oort cloud or the KB. In the light of all these new developments on the origin and evolution of orbits of comets, SW1 undoubtedly is a unique object that deserves attention besides the interest it has always aroused for its peculiar brightness behaviour.

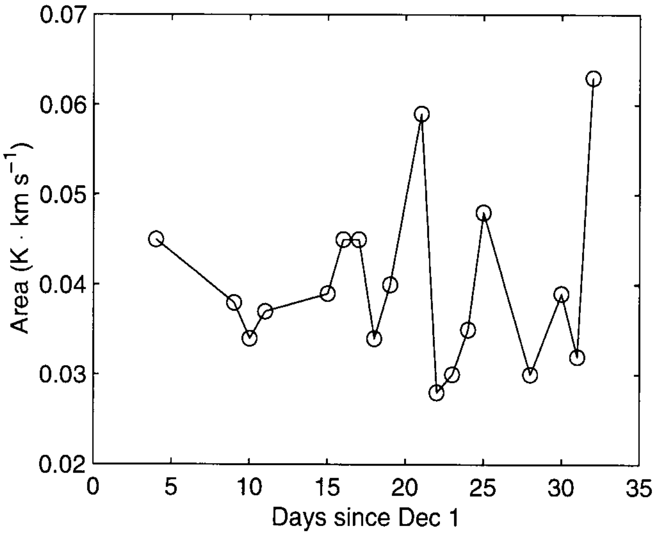

Figure 1: CO production in comet SW1 measured during the month of December 1996. The comet was observed during a period we can qualify, based on the comet total magnitude, as of "low" or "minimal" activity, the so-called "quiescent state".

SW1 is known since its discovery in 1927 for its numerous and unpredictable bursts of activity, some of which bring its magnitude down to 10–11 from a state of much lower brightness long