COSMOLOGY – FORMATION AND EVOLUTION OF GALAXIES AND ACTIVE NUCLEI

Alberto Franceschini

I started active work in the field of observational and theoretical cosmology since 1985, roughly in concomitance with the first space infrared mission IRAS. The main road I pursued was to explore paths for galaxy formation and evolution using data from all available wavebands. The exploitation of long wavelength surveys on one side, and hard X-ray data on the other, in particular, turned out to be critical for understanding the main evolutionary phases following interactions and mergers among galaxies. During these phases, the formation of a galaxy or an Active Galactic Nucleus inside it happen within a thick gaseous and dusty medium (wherein stars are very efficiently formed and AGNs easily fuelled), which explains the relevance of exploiting observations in the far-infrared and hard X-rays to get rid of extinction/absorption. With these premises, my team and I started to work for the Infrared Space Observatory through institutional collaborations (Sect. 7 below). The main results have been obtained after the end of the mission, during 2000 and subsequent years, and reported in a number of papers and conferences/meetings: they concern the first decisive evidence for very strong evolution back in cosmic time for the far-IR emissivity of galaxies up to cosmic epochs corresponding to z=1, and the evidence for a phase of strong activity of star formation and AGN fuelling from z=0.7 to z=2. From all these studies it very clearly emerged the need for complementing cosmological information on galaxies at high redshifts collected in the optical from ground telescopes with that provided by space telescopes observing in the mid-IR, far-IR and sub-mm. Our main finding was that, without this widening of the observational perspective, the main evolutionary phases of galaxies would be lost.

Our team then: entered important collaborations to use data from the NASA "Great" IR Observatory Spitzer; is currently working in preparation for the ESA Cornerstone mission Herschel; exploited the new relevant space facilities of X-ray astronomy (XMM-Newton and Chandra) and the Hubble Space Telescope Advanced Camera for Surveys. When I was member of the ESA Astronomy Working Group, I promoted the entrance of Europe in the NASA new generation space telescope JWST.

As of today, our publication record during 2000-2004 includes 60 on refereed journals and 45 as conference proceedings, all papers either led by us or in which we had active participation. Altogether our publications in this period collected more than 1400 ADS citations.

Project 1: PARTICIPATION IN THE INFRARED SPACE OBSERVATORY MISSION AND ITS PROGRAM OF COSMOLOGICAL SURVEYS. GALAXY EVOLUTION AT LONG WAVELENGTHS.

During the 1990's, I have worked as co-Investigator of the IR camera ISOCAM on board the INFRARED SPACE OBSERVATORY (ISO). My contribution started when I was associate astronomer of the Astronomical Observatory in Padova (this latter provided elements for the ground segment to the instrument). My contribution concentrated in particular on studying potential capabilities of the ISO mission for cosmological observations, based on IRAS data available at that time.

Based on my analysis, and in collaboration with a team of astrophysicists of the Service d'Astrophysique de Saclay (including current ESO Director General, C. Cesarsky), it has been possible to plan for a systematic program of cosmological surveys with the ISO mid- and far-IR cameras. Altogether this set of observations has taken more than 20% of the whole mission time.

The main results have been reported in my paper of 2001 (Franceschini et al. 2001, “A long-wavelength view on galaxy evolution from deep surveys by the Infrared Space Observatory”, A.&A. 378, 1, >100 ADS citations in 3.5 yrs, upper 0.3% quartile of papers in astronomy), where we included in our analysis also data taken with millimetric telescopes at longer wavelengths. These observations indicated extremely high rates of evolution for IR galaxies, exceeding those measured for galaxies at other wavelengths and comparable or larger than the rates observed for quasars. We also matched the integrated emission by IR galaxies at any redshifts with the observed spectral intensity of the extragalactic IR background (CIRB), as a further constraint. The multi-wavelength statistics on IR galaxies was explained by us assuming for the bulk of the population spectral energy distributions (SED) as typical for starbursts, which we take as an indication that stellar, rather than AGN (see also Fadda et al. 2002, “The AGN contribution to mid-infrared surveys. X-ray counterparts of the mid-IR sources in the Lockman Hole and HDF-N”, A&A 383 838) activity powers IR emission by faint galaxies. According to our analysis (see also Elbaz et al. 2002, “The bulk of the cosmic infrared background resolved by ISOCAM”, A&A 384 848), the deep ISO surveys at 15 micron have resolved more than 50% of the bolometric CIRB intensity: the faint ISO 15 micron source samples, relatively easy to identify in deep optical images, then allowed us to investigate the origin of the CIRB background. From our fits to the observed optical-IR SEDs, these objects appeared to mostly involve massive galaxies hosting luminous starbursts (SFR ~ 100 Msun/yr). The evolutionary scheme that we inferred from these data considered a bimodal star formation (SF), including a phase of long-lived quiescent SF, and enhanced SF taking place during transient events recurrently triggered by interactions and merging. We interpreted the strong observed evolution as an increase with z of the rate of interactions between galaxies (density evolution) and an increase of their IR luminosity due to the more abundant fuel available in the past (luminosity evolution): both factors enhance the probability to detect a galaxy during the ``active'' phase at higher z. Very schematically, we associated the origin of the bulk of the optical/NIR background to the quiescent evolution, while the CIRB is interpreted as mostly due the dusty starburst phase. The latter possibly leads to the formation of galaxy spheroids, when the dynamical events triggering the starburst re-distribute already present stellar populations. The large energy contents in the CIRB and optical backgrounds are not easily explained, considering the moderate efficiency of energy generation by stars: we suggested that a top-heavy stellar IMF associated with the starburst phase (and compared with a more standard IMF during the quiescent SF) would alleviate the problem. The evolution of the IR emissivity of galaxies from the present time to z ~ 1 is so strong that the combined set of constraints by the observed z-distributions and the CIRB spectrum impose it to turn-over at z>1: scenarios in which a dominant fraction of stellar formation occurs at very high-z were not supported by our analysis.

Our analysis of the Infrared Space Observatory cosmological surveys continued more recently with the work of my PhD students in Padova. Particularly relevant our efforts to reduce and analyse the whole ISO database from the ELAIS wide-area survey based on improved reduction algorithms (Vaccari et al. 2005 MNRAS ; Rodighiero et al. 2004, "ISOCAM observations in the Lockman Hole . II. The 14.3 μm deep survey: Data reduction, catalogue and source counts", A & A 427, 773; Fadda et al. 2004, "ISOCAM observations in the Lockman Hole. I. The 14.3μm shallow survey: Data reduction, catalogue, and optical identifications", A&A 427, 23), and part of the ISOPHOT far-infrared survey database (Rodighiero et al. 2003, "A far-infrared view of the Lockman Hole from ISO 95-μm observations - I. A new data reduction method", MNRAS 343, 1155; Rodighiero & Franceschini, A., "ISOPHOT 95 micron observations in the Lockman Hole. The catalogue and an assessment of the source counts”, 2004, A&A 419, L55).

A variety of complementary observations have been carried out in the ELAIS fields, particularly noticeable these in X-rays (Manners et al. 2004, "Mid-infrared sources in the ELAIS Deep X-ray Survey", MNRAS 355, 97).

Project 2: PARTICIPATION IN THE SPITZER SPACE TELESCOPE LEGACY PROGRAM "WIDE-AREA INFRARED EXTRAGALACTIC " SURVEY (SWIRE) AND COMPLEMENTARY OBSERVATIONS.

As a natural continuation of the activities carried out in the framework of the ISO mission and thanks to the expertises that my team and me have acquired from that, I have taken part as co-Investigator in a worldwide collaboration to exploit the new generation NASA space observatory Spitzer. We have been successful in applying and obtaining to perform a large-area cosmological survey (SWIRE), which is the largest observing program among those of the Spitzer Legacy. The project aimed at surveying in 7 bands from the near- to mid- and far-IR a total of 49 sq.deg. in 6 sky areas, including those with the minimum local background emission (Lockman, CDFS, XMM/LSS, ELAIS N1, N2, S1). The observations started end of 2003 and have been completed in January 2005. This enormous project, using 851 hours of observing time, has triggered a variety of complementary observations needed for the identification and full characterization of the IR-selected sources. In particular, our Padova group has committed itself for acquiring optical multiband observations in an area of 5 sq.degrees in the field ELAIS S1 in BVRIz, based on an ESO Large Program running since ESO Obs. Period 68 (ESIS, P.I. A. Franceschini), including both WFI 2.2m and VIMOS/VLT imaging data.

Our Padua group ha taken responsibilities for the scientific exploitation of SWIRE data in the fields of the formation and evolution of spheroidal galaxies, the galaxy evolutionary mass function, and the phenomenon of type-1 and –2 AGNs.
Although the SWIRE survey project observations from space have started only 1 year ago, we have already obtained interesting results from the combination of Spitzer and Chandra X-ray data in a region of ELAIS N1 that british collaborators and us previously obtained (see Sect. 1). Based on these data we were able to determine the broad-band spectral properties and statistics of AGNs of the various kinds in a flux-limited X-ray sample (Franceschini et al. 2005, "A Complete Multiwavelength Characterization of Faint Chandra X-ray Sources Seen in the Spitzer Wide-Area IR Extragalactic (SWIRE) Survey", Astronomical Journal AJ 129, 2074).

Project 3: THE HERSCHEL SPACE OBSERVATORY: COLLABORATION IN THE FOCAL PLANE INSTRUMENT SPIRE. ORGANIZATION OF THE PROGRAM OF COSMOLOGICAL SURVEYS, TO MEASURE THE BOLOMETRIC EMISSION BY COSMIC SOURCES IN THE FAR-IR AND SUB-MM.

The Herschel Space Observatory (HSO) will be in 2007 the very first 4-meter class astronomical telescope in space. It will be dedicated to a sky exploration in the far-IR and sub-mm, for the first time with sufficient angular resolution thanks to the large primary photon collector (I worked at this project since 1996, when nominated by ESA as an expert to evaluate potential scientific return by such a mission). Since the beginning, Italy was among the partner members, by contributing the on-board computers and the on-board and ground-segment software, and part of the Instrument Control Centers. I was one of the 3 italian co-Investigators of the mission, following in particular one the the 3 focal-plane instruments, the sub-mm imaging/spectrometer SPIRE.

HSO will provide the capability to observe the universe at long-wavelengths deep enough to detect and measure the dust-reradiation part of the e.m. spectrum of galaxies. It turns out (see Sects. 1 & 2 above) that during the main evolutionary phases of galaxies (probably triggered by galaxy mergers and interactins) the bulk of the energy output by stars and by the central nuclear AGN is absorbed

by dust and re-emitted at long wavelengths (50 to 500 μm), which are very well covered by the HSO mission. The corrections to the optical fluxes needed to account for such dust reprocessing are enormous and the underline physics extremely complex, such that only a direct measure by HSO will allow to determine the detailed physical processes occurring during these phases.

We are currently hard working not only at the organization aspects of the instrument/observatory, but also to define a plan for cosmological surveys to carry out as Guaranteed Time and Open Time observations. The ASI is supporting financially this effort.

Project 4: THE ACTIVE GALAXY PHENOMENON: OBSERVATIONS AND MODELLISTIC ANALYSES. COSMIC BACKGROUND RADIATIONS IN THE INFRARED AND X-RAYS.

The activity of galaxies concerns transient phenomena occurring during the galaxy lifetime, consequence of a rapid gas inflow into the nucleus, which is either processed in stars, or is accreted by the strong gravitational field of a supermassive Black Hole (BH), or both. Large amounts of energy are then produced over periods of 107-108 yrs, in the forms of radiation, ultra-relativistic particles, and plasma outflows. This phenomenon has important relationship and consequences for cosmology: it likely follows important morpological transformations like the generation of stellar bulges and of a nuclear supermassive BH, is responsible for the background radiations in the Gamma, X-ray, IR and radio bands.

Altogether, Galaxy Activity deals with the most relevant evolutionary phases of galaxies. This branch of Astrophysics has experienced a dramatic evolution during the last 4 decades, thanks in particular to new observational techniques, both from space and from ground, progressively widening the e.m. spectral domain accessible to observation. Following the outcomes of our projects in Sects. 1 and 2, showing that this phenomenon was extremely more frequent during the past cosmic history than it is now, we have undertaken at the end of 1990's a long-term project to investigate with a variety of approaches the physical nature of the e.m. emission by Active Galaxies, trying to discriminate between the (stellar) thermonuclear from the (nuclear) gravitational contributions.

Three our main investigation paths: hard X-ray observations to detect the primary unabsorbed AGN flux; IR vs. optical spatially-resolved spectroscopy, and optical spectro-polarimetry. As for the first one, we were leading an observing campaign with XMM-Newton of a sample of local Ultraluminous IR Galaxies (ULIRGs) considered to be the local representatives of the Active Galaxies high-z counterparts (Franceschini et al. 2003, "An XMM-Newton hard X-ray survey of ultraluminous infrared galaxies", MNRAS 343, 1181; Franceschini, 2000, "BeppoSAX uncovers a type-2 QSO in the hyperluminous IR galaxy IRAS 09104+4109", A&A 353, 910). For the second one we have led and carried out an observing program with ISAAC and FORS on ESO/VLT of faint high-z Active Galaxies discovered by ISO (Franceschini et al. 2003, "Infrared spectroscopy of faint 15 micron sources in the Hubble Deep Field South: first hints at the properties of the sources of the IR background", A&A 403, 501; Berta et al., 2003, "Spatially-resolved spectrophotometric analysis and modelling of the Superantennae", A&A 403, 119), showing for the first time that these objects are massive luminous galaxies, likely members of galaxy groups. We also actively participated in a program of L-band ISAAC spectroscopy with astronomers in Arcetri (Risaliti et al. 2003, "Revealing the Active Galactic Nucleus in the Superantennae through L-Band Spectroscopy", ApJ 595, L17). The general and most relevant outcome of these studies was to show for the first time uncontroversial evidence that the stellar and gravitational processes are concomitant in Active Galaxies, or at least part of a sequence of events following the dynamically-triggered "activation", a

result supporting the evidence of a relationship between supermassive BH's and the host galaxy stellar populations.

Finally, we have related the Active Galaxy phenomenon with the e.m. relics currently observable in the form of cosmological background radiations in radio, IR, and X-rays. The bulk of these backgrounds are interpreted as the integrated contributions of the past Galaxy Activity: relevant constraints ensue the comparison of the background intensity and resolved source counts. The X-ray and IR backgrounds are found, in particular, as the manifestation of the AGN and starburst phases, respectively (Franceschini, Braito, Fadda, 2002, "Origin of the X-Ray Background and AGN Unification: New Perspectives", MNRAS 335, L51).

Project 5: PARTICIPATION IN THE HST "COSMOS" AND GOODS PROJECTS OF COSMOLOGICAL SURVEYS WITH HST AND RELATED OBSERVATIONS: ORIGIN OF THE HUBBLE MORPHOLOGICAL SEQUENCE AND ITS COSMOLOGICAL EVOLUTION.

The implementation of the Advanced Camera for Surveys (ACS) at the focal plane of the HST has been one of the recent milestones for observational cosmology. The ultimate spatial resolution of ACS provides the unique opportunity to investigate the origin of the morphological structure of galaxies during the past cosmic epochs. I took full advantage of this new important facility by participating as co-Investigator in the largest HST cosmological survey, the COSMOS project, using 600 HST orbits on a 2 sq.deg. contiguous area. Based on this, a large effort of complementary observations, from radio, to optical, to X-rays has started and continues as of now. I am collaborating in most of these efforts.

In parallel, I started since the end of 1990's a long-standing program in Padova dedicated to ths development of expertises and new tools for the investigation of structures and morphologies of faint galaxies at high redshifts (also in collaboration with astronomers of the Padua Observatory). A PhD student (P. Cassata) has been addressed in this field. This work has been performed originally on WFPC2 data on HDFs (Franceschini et al. 1998, "Early-type galaxies in the Hubble Deep Field: the star formation history" ApJ 506, 600; Rodighiero, Franceschini, Fasano, 2001, "Deep Hubble Space Telescope imaging surveys and the formation of spheroidal ghalaxies" MNRAS 324, 491), where we found a remarkable lack of spheroidal galaxies at redshifts $z>1.3$. Then we used very deep ACS data available in a SWIRE field (Hatziminouglou et al. 2005, MNRAS in press), imaging and spectroscopic data in the K20 sample (Cassata et al. 2005, "The evolution of the galaxy B-band rest-frame morphology to $z\sim 2$: new clues from the K20/GOODS sample", MNRAS 357, 903), and finally deep ACS images and multiband data from GOODS to extend this investigation to larger areas, fainter magnitudes, higher redshifts. All these analyses seemed to support our original intuition about a strong evolution of the (spheroidal) galaxy mass function at $z>1$, in the sense of a decrease of the massive galaxy population at these z.

Project 6: MODELLISTIC STUDIES OF GALAXY FORMATION IN THE CONTEXT OF THE HIERARCHICAL CLUSTERING THEORY.

We have recently started a project to investigate possible interpretations of our observations based on physical models for the origin of structures. A current day reference for the latter is the Cold Dark Matter (CDM) Hierarchical Clustering scenario, in which structures on larger and larger scales form progressively from aggregtion of smaller units at increasing cosmic time. Our results in the previous Sects., showing strong galaxy activity during a protracted cosmic era down to $z\approx 0.5$, seemed in qualitative agreement with CDM-based expectations. There is however accumulating

observational evidence that the formation of most luminous, more massive galaxies and AGNs tend to form on shorter cosmological timescales than the lower mass-luminosity systems (e.g. Franceschini et al., 1999, "On the relationship between galaxy formation and quasar evolution", MNRAS 310, L5), which is rather at variance with the simplest prediction of Hierarchical Clustering models.

We are currently exploring with dedicated effort by our team in Padua how much these findings can be explained as a result of the differential effects of evolution in different cosmic environments (the denser ones, where the more massive systems form through merging, collapse and form galaxies first, the shallower taking the whole Hubble time for doing it), or an effect of energy feedback, or else.

Personnel:

Franceschini Alberto	(Professore Ordinario)
Rodighiero Giulia	(Assegnista)
Prouton Oliver	(Post-doc RTN Network POE)
Manners James	(Post-doc RTN Network POE)
Clemens Marcel	(Post-doc Marie Curie)
Braito Valentina	(PhD student)
Berta Stefano	(PhD student)
Cassata Paolo	(PhD student)
Fritz Jacopo	(PhD student)
Ricciardelli Elena	(PhD student)
Aussel Herve'	(Post-doc RTN Network on Galaxy Formation)

Collaborations:

1) Service d'Astrophysique, Centre d'Etudes Atomiques, Paris (contact : dr. C. Cesarsky)
2) Imperial College of Science and Medicine, London (contact: prof. M. Rowan-Robinson)
3) Infrared Processing and Archiving Center (IPAC), Pasadena (contact: dr. C. Lonsdale)
4) Instituto de Astrofisica de Canarias (IAC), Spain (contact: dr. I. Perez Fournon)
5) Max-planck Institute fur Extraterrestriche Physik (MPE), Garching (contact : dr. D. Rigopoulou)
6) University of Cardiff, IFSI/INAF Roma, Osservatorio Astronomico di Padova, per il progetto Herschel (contacts: dr. M. Griffin, dr. P. Saraceno, dr. G. De Zotti)

Plus a very large number of non institutional collaborations

Research Products:

2000: 9 pubblicazioni con referee + 8 pubblicazioni senza referee
2001: 10 pubblicazioni con referee + 9 pubblicazioni senza referee
2002: 12 pubblicazioni con referee + 4 pubblicazioni senza referee
2003: 11 pubblicazioni con referee + 12 pubblicazioni senza referee
2004: 18 pubblicazioni con referee + 9 pubblicazioni senza referee

List of 5 most representative publications:

1) Franceschini, A., Bassani, L., Cappi, M., Malaguti, G., Persic, M., Palazzi, E., 2000, BeppoSAX uncovers a type-2 QSO in the hyperluminous IR galaxy IRAS 09104+4109, Astronomy and Astrophysics 353, 910.

2) Franceschini, A., H. Aussel, Cesarsky C., Elbaz D., Fadda D., 2001, A long-wavelength view on galaxy evolution from deep surveys by the Infrared Space Observatory, Astronomy and Astrophysics 378, 1

3) Franceschini, A., Braito, V., Persic, M., Della Ceca, R., Bassani, L., Cappi, M., Malaguti, P., Palumbo, G. G. C., Risaliti, G., Salvati, M., Severgnini, P., "An XMM-Newton hard X-ray survey of ultraluminous infrared galaxies", 2003, MNRAS 343, 1181

4) Franceschini, A., Berta, S., Rigopoulou, D., Aussel, H., Cesarsky, C. J., Elbaz, D., Genzel, R., Moy, E., Oliver, S., Rowan-Robinson, M., Van der Werf, P. P., "Infrared spectroscopy of faint 15 micron sources in the Hubble Deep Field South: First hints at the properties of the sources of the IR background", 2003, A&A 403, 501

5) Franceschini, Braito, Fadda, 2002, "Origin of the X-Ray Background and AGN Unification: New Perspectives", MNRAS 335, L51