The Drama of Galaxies in Close Interaction

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One of the most fundamental issues of modern astronomy is the question of the origin and early evolution of galaxies. The deeper we penetrate into the past history of the universe, the more important these questions seem to be. In particular, we may ask why the galaxies show up in so many different shapes and if the morphology of a galaxy may be substantially altered during the evolution of the universe. In this context, the galaxies which have a peculiar, i. e. non-Hubble, morphology, have attracted special attention. Among these objects, we find the interacting galaxies, which constitute approximately 5% of all galaxies.

Many interacting galaxies were once thought to be objects in rapid, violent expansion and were labelled as "post-eruptive" by Fritz Zwicky. Today, however, few people agree with this description. Instead, as has been shown by numerical modelling of close encounters between galaxies, most of these peculiar forms may be explained as effects of gravitational interaction, and we have strong reason to believe that the state of interaction may be one important stage in the evolution of many of the otherwise normal galaxies. This stage may be quite short ($\lesssim 10^9$ years) before the components of the system finally merge into one single object, thereby more or less hiding its past history. We do not know how such a merging will affect the morphology of the galaxies and neither do we know in any detail how it will affect a variety of other parameters such as star formation rate, gas/dust content and distribution, angular momentum or velocity distribution of the stars. We may assume, however, that the changes in many cases will be dramatic.

Thus, although it seems probable that many of the single galaxies that we observe today are merger remnants, our knowledge is too limited for us to be able to pick them out. It is therefore important to continue the study of galaxies in close interaction on a broad base.

Bursts of Star Formation and Nuclear Activity

In Uppsala the study of interacting galaxies in the southern hemisphere started a few years ago. Today A. Ekman, A. Lauberts and myself are working on the project. During the first years of observations, most of the data were collected at the ESO 1 m and 1.5 m telescopes and resulted in a large amount of UBV data, radial velocities and basic spectral data. A look at the radial velocity data revealed that in practically all of the observed cases the components of the systems could well be gravitationally bound. This result also implies that the galaxies normally were born side by side, although the separation between the components may have been larger in the past.

The UBV data showed that the interacting galaxies in the mean were bluer than normal, which in most cases probably is a natural consequence of the burst of star formation that is initiated by the interaction. One such unusually blue system, ESO 255-IG07, is shown in Fig. 1a. Here we see four galaxies embedded in a common halo. Although none of these galaxies is of late Hubble type, the UBV colours (U-B = –0.22, B-V = 0.54) resemble those of late-type spirals or irregulars. Spectra of these galaxies taken with the ESO 3.6 m and 1.5 m telescopes show that they contain very extended regions of ionized gas, bridging the gaps between the galaxies. These areas do not have the patchy structure characteristic of associations of H II regions, but resemble huge regions of shock-heated turbulent gas, which has been stirred up as a consequence of the interaction.

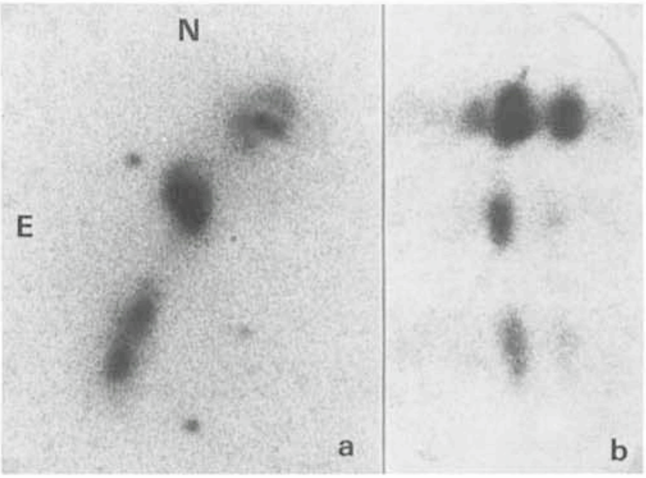

Fig. 1a: *ESO 255-IG07. 60ᵐ prime focus plate obtained at the ESO 3.6 m telescope. Baked IIa-O emulsion + GG 385 filter.*
Fig. 1b: *The Hα region of spectra of the different components of ESO 255-IG07. The vertical scale is the same as that in Fig. 1a. Note the double structure of Hα of the northernmost component. Image tube at the Cassegrain focus of the ESO 3.6 m telescope.*

From the spectral line data, we have found evidence for shock-heating and large-scale motions of the gas clouds in the central parts of the northernmost galaxy. As can be seen from Fig. 1b, showing the spectral region around Hα, the hydrogen line is double, indicating outward flow of discrete clouds with velocities of about 150 km s^{-1}. From the [S II] λ6717/λ6731 line ratio, we know that the gas density in the central region is fairly low, about 400 cm^{-3}.

It is interesting to note that this galaxy has other features in common with galaxies with active nuclei. The form of the Balmer decrement and the strong Na I D lines in absorption imply that it contains huge amounts of dust, causing an absorption of about 4^m in blue. If this envelope would disperse, we would see a brilliant small nucleus of an unusually high surface brightness. A detailed analysis of the properties of this system will soon appear in *Astronomy and Astrophysics.*

First Act: A Close Encounter in Slow Tempo

Naturally, it would be interesting to know more about the features of the nuclei of interacting galaxies in relation to the often very chaotic state of the interstellar medium, in the cases where the components have interpenetrated

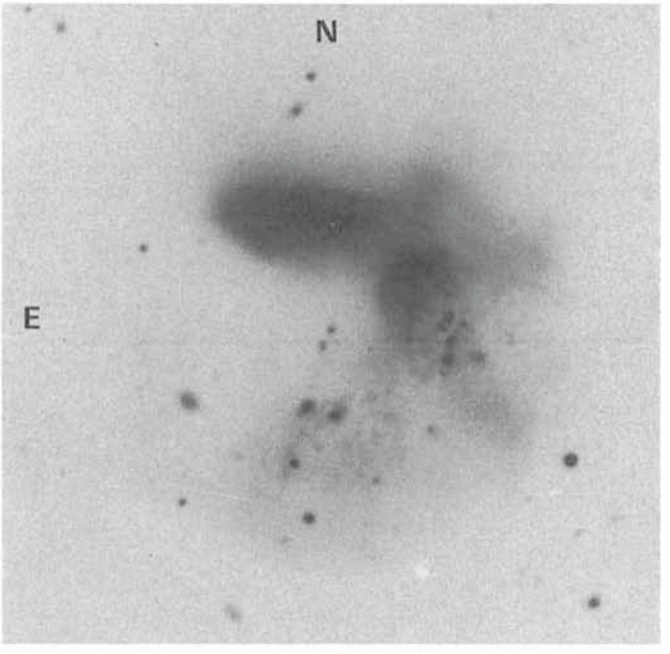

Fig. 2: *NGC 454. 90^m prime focus plate at the ESO 3.6 m telescope. Baked IIIa-J + GG 385 filter.*

deeply. At the moment, therefore, we have devoted much of our attention to the study of such systems, one of which is shown in Fig. 2. This blue photograph of NGC 454 was obtained at the prime focus of the ESO 3.6 m telescope. Here we witness how two galaxies, one of early and one of late Hubble type, have advanced into the merging state. As can be seen from the deep blue photo, although mostly exceedingly faint, the system is limited by a remarkably regular envelope.

Fig. 3 shows spectra of the central regions of the two components of NGC 454, obtained with the Image Dissector Scanner at the ESO 3.6 m telescope. The westernmost galaxy shows a spectrum typical of H II regions and has a very blue continuum. This probably originates from hot stars, rapidly being formed in the vicinity of the nucleus. The eastermost component also shows the nebular [O III] lines in emission, but no Hβ in emission – a remarkable circumstance. Either it means that the excitation is high, which is contradicted by the absence of high ionization lines, like He II λ4686, or the underlying stellar absorption is strong. We favour the last interpretation, since the Balmer lines in absorption are clearly seen at the blue end.

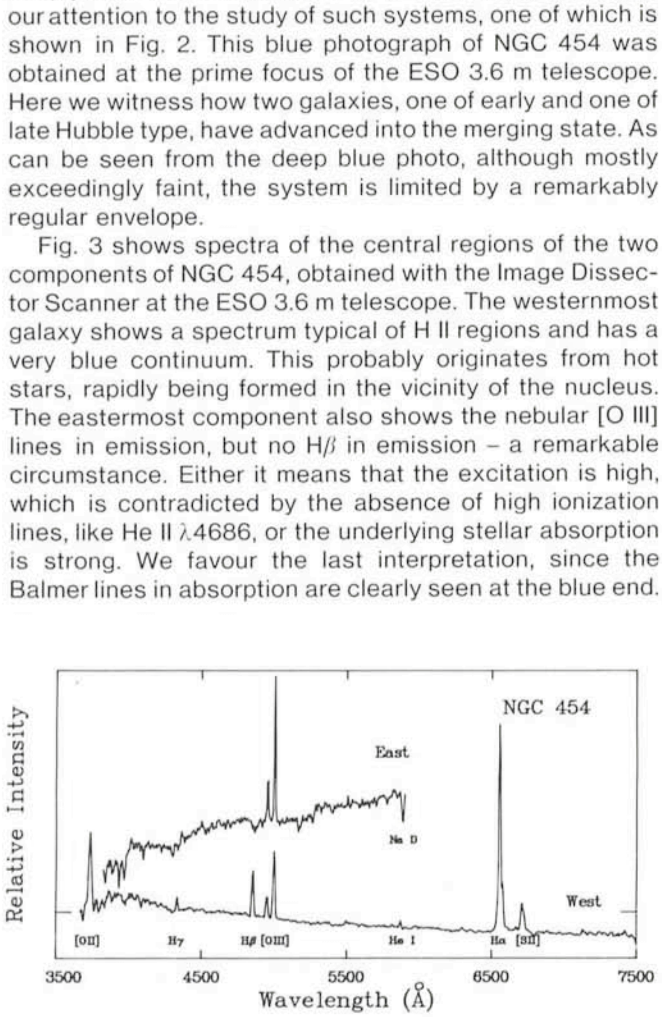

Fig. 3: *Spectra of the two nuclei of NGC 454, obtained with the IDS at the ESO 3.6 m telescope.*

Thus, young stars may give an important contribution to the light of the blue region also in this case. The red colour of the continuum is probably due to reddening by dust in the central region. The strong Na I D and probably also Ca II H and K are thus largely interstellar in origin.

According to the UBV data, NGC 454 east mainly contains old stars. Most of the star formation activity is thus confined to the nucleus. From where then does the fuel of this star formation come? It seems likely that it is supplied by the gas-rich companion galaxy, or that unprocessed halo gas, through the effects of the interaction, is accreted onto the nucleus, thereby initiating the star formation.

Final Act: The Two Become One

Systems like NGC 454 make it tempting to speculate about what a completely merged system of this type could look like. It seems that it should have a fairly regular shape and an early stellar population dominating the light of the nucleus, if the merging took place recently. The gas content should have gone down considerably, due to the high rate of star formation. Still, it could be normal, in relation to the morphological type, if the process of merging has caused a drift towards earlier Hubble types, as expected.

About 20% of all disturbed galaxies appear as single, isolated galaxies. A few of these may be the objects we are looking for, and Fig. 4 shows one possible candidate, ESO 341-IG04, although one may think of alternative interpretations of the peculiar properties of this system. The total dimension is about 50 kpc and $M_V = -21.9$ (H_O = 75 km^{-1} Mpc^{-1}), which is unusually bright. Morphologically, we notice the structures of the outer regions, which may be remnants of spiral arms from a galaxy that has participated in the merging.

In Fig. 5 we see the spectrum of the central region. Despite the early morphological type, which suggests that the light should be dominated by that of old stars, the spectrum comes from a fairly young stellar population, showing strong Balmer lines in absorption. At Hα, emission is also seen. A long-exposed spectrum obtained at the 1.5 m telescope shows that the young population dominates the light out to about 3 kpc from the centre. The corrected UBV colours (U-B = 0.36, B-V = 0.70) are practically independent of aperture and deviate strongly from the two-colour relation of normal galaxies. The colours are not abnormal, however, compared to colours from models of galaxies invoking an intense burst of star formation in an old stellar population (Larson and Tinsley: 1978, *Astrophysical Journal* **219**, 45). The best agreement is found if the maximum of the burst occurred about $2 \cdot 10^9$ years ago, in agreement with the timescale of the merging and the composite spectral type.

Near-infrared Photometry

As an additional source of information about the conditions in the central regions of interacting galaxies, we have used broadband near-infrared photometry. Using the InSb detector at the ESO 1 m telescope we have obtained JHKL magnitudes at 12'' aperture. Fig. 6 shows the results combined with the UBV data, for NGC 454 and ESO 341-IG04. Normally, the IR continuum of galaxies, being

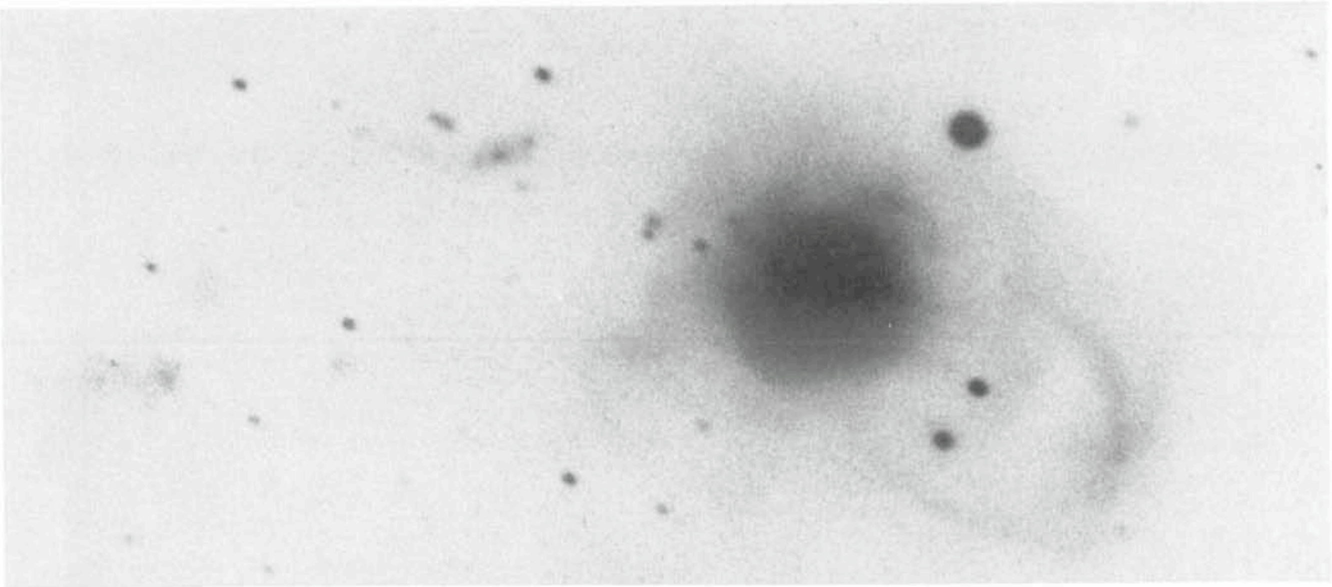

Fig. 4: *ESO 341-IG04. 75ᵐ prime focus plate at the ESO 3.6 m telescope. Baked IIIa-J + GG 385 filter.*

dominated by late-type giants, reaches a maximum around H. NGC 454 east, however, keeps on rising towards lower frequencies after a local maximum. This part of the continuum probably originates from dust that has been heated by hot stars in the nuclear region, in agreement with the description given above. ESO 341-IG04, although having a K excess as compared to normal galaxies, seems to possess considerably less dust in front of the hot stars, or the heating of the dust is less efficient. The fact that Na I D is strong seems to favour the last alternative, but the analysis is still very preliminary.

Another important aspect of IR observations of interacting galaxies is the possible link to Seyfert 2 galaxies, which also show spectra that rise steeply into the infrared. The mechanism behind this radiation is still in many cases unclear.

Present Status and Future Observations

During the last few years we have obtained a large amount of detailed spectroscopic, photographic and photometric data of interacting galaxies. Most of these objects are cases where galaxies of fairly ordinary dimensions and luminosities are involved, as in the cases discussed above. Another subgroup is characterized by aggregates of small (young?) irregular blue objects, which seem to be underabundant of heavy elements. The analysis of all these data is now in full progress. An exciting future project would be to use the results of the analysis in a search for "merger remnants" among galaxies resembling ordinary E – S0's. This would not have much connection with the models of cluster cannibalism, since these so far only involve regular gas-free galaxies. As concerns the fate of merging spiral galaxies, it seems that the breakthrough in the understanding of these objects must be preceded by extensive observations over the whole accessible wavelength region.

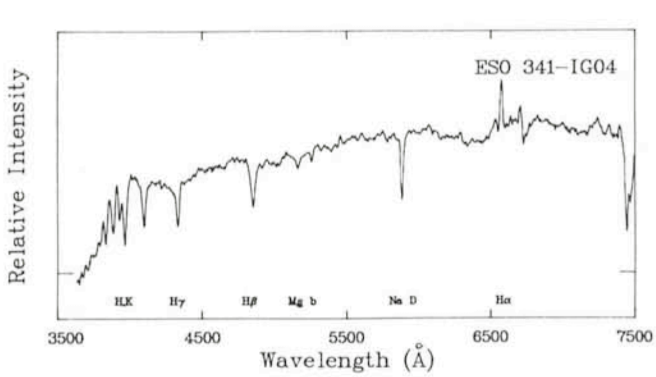

Fig. 5: *Spectrum of centre of ESO 341-IG04, obtained with the IDS at the ESO 3.6 m telescope.*

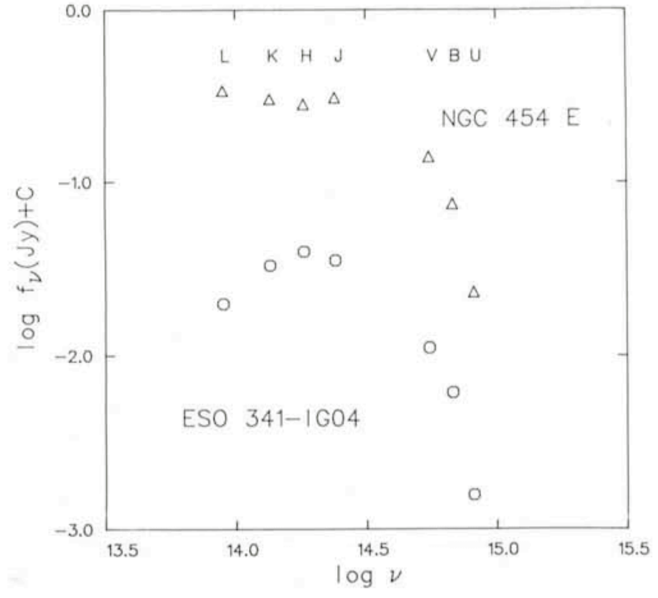

Fig. 6: *Photoelectrical broadband photometry of NGC 454; aperture: 12" (JHKL) and 22" (UBV), and ESO 341-IG04; aperture: 12" (JHKL) and 11" (UBV). C = 1 for NGC 454 and C = 0 for ESO 341-IG04.*