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Interactions as a driver of galaxy evolution

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François Schweizer

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Interactions as a driver of galaxy evolution **as a driver of galaxy**
BY FRANÇOIS SCHWEIZER

The Observatories of the Carnegie Institution of Washington,
 The Observatories of the Carnegie Institution of Washington,
 R12 Scate Bashara Street, Basedone, CA 01101, USA *813 Santa Barbara Street, Pasadena, CA 91101, USA*

 813 Santa Barbara Street, Pasadena, CA 91101, USA
 \Box Gravitational interactions and mergers are shaping and reshaping galaxies through-
 \Box out the observable Universe. While observations of interacting galaxies at Gravitational interactions and mergers are shaping and reshaping galaxies through-
out the observable Universe. While observations of interacting galaxies at low red-
shifts vield detailed information about the processes a Gravitational interactions and mergers are shaping and reshaping galaxies through-
out the observable Universe. While observations of interacting galaxies at low red-
shifts yield detailed information about the processes a out the observable Universe. While observations of interacting galaxies at low redshifts yield detailed information about the processes at work, observations at high redshifts suggest that interactions and mergers were muc shifts yield detailed information about the processes at work, observations at high redshifts suggest that interactions and mergers were much more frequent in the past. Major mergers of nearby disc galaxies form remnants t redshifts suggest that interactions and mergers were much more frequent in the past.
Major mergers of nearby disc galaxies form remnants that share many properties
with ellipticals and are, in essence, present-day proto-el Major mergers of nearby disc galaxies form remnants that share many properties
with ellipticals and are, in essence, present-day proto-ellipticals. There is also tan-
talizing evidence that minor mergers of companions may with ellipticals and are, in essence, present-day proto-ellipticals. There is also tantalizing evidence that minor mergers of companions may help build bulges in disc
galaxies. Gas plays a crucial role in such interactions talizing evidence that minor mergers of companions may help build bulges in disc
galaxies. Gas plays a crucial role in such interactions. Because of its dissipative
nature, it tends to get crunched into molecular form, tur galaxies. Gas plays a crucial role in such interactions. Because of its dissipative nature, it tends to get crunched into molecular form, turning into fuel for starbursts and active nuclei. Besides the evidence for ongoing nature, it tends to get crunched into molecular form, turning into fuel for starbursts and active nuclei. Besides the evidence for ongoing interactions, signatures of past interactions and mergers in galaxies abound: tidal discs and bulges, polar rings, systems of young globular clusters, and ageing starinteractions and mergers in galaxies abound: tidal tails and ripples, counter-rotating
discs and bulges, polar rings, systems of young globular clusters, and ageing star-
bursts. Galaxy formation and transformation is clea discs and bulges, polar rings, systems of young globular clusters, and ageing star-
bursts. Galaxy formation and transformation is clearly a prolonged process, occurring
up to the present-day. Overall, the currently availa bursts. Galaxy formation and transformation is clearly a prolonged process, occurring
up to the present-day. Overall, the currently available observational evidence points
towards Hubble's morphological sequence being main up to the present-
towards Hubble's
merger damage.

ge.
Keywords: galaxy interactions; mergers; elliptical formation;
bulge formation: starbursts: quasars alaxy interactions; mergers; elliptical f
bulge formation; starbursts; quasars

1. Introduction

1. Introduction
Ever since Hubble (1936) published his famous 'sequence of nebular types' (also
known as the tuning-fork diagram) the question has been what determines the Ever since Hubble (1936) published his famous 'sequence of nebular types' (also
known as the tuning-fork diagram), the question has been: what determines the
position of a galaxy along this sequence? And why are galaxies a Ever since Hubble (1936) published his famous 'sequence of nebular types' (also known as the tuning-fork diagram), the question has been: what determines the position of a galaxy along this sequence? And why are galaxies a known as the tuning-fork diagram), the question has been: what determines the position of a galaxy along this sequence? And why are galaxies at one end of the sequence disc shaped and at the other end ellipsoidal? Was this position of a galaxy along this sequence? And why are galaxies at one end of the sequence disc shaped and at the other end ellipsoidal? Was this shape dichotomy imprinted during an early collapse phase of galaxies, or did sequence disc shape
imprinted during are
quent evolution?
Work begun seve printed during an early collapse phase of galaxies, or did it arise through subse-
ent evolution?
Work begun several decades ago by Zwicky (1956), Arp (1966), Alladin (1965)
d Toomre & Toomre (1972), among others, has led

quent evolution?
Work begun several decades ago by Zwicky (1956), Arp (1966), Alladin (1965)
and Toomre & Toomre (1972), among others, has led to growing evidence that grav-
itational interactions between neighbouring gala Work begun several decades ago by Zwicky (1956), Arp (1966), Alladin (1965)
and Toomre & Toomre (1972), among others, has led to growing evidence that grav-
itational interactions between neighbouring galaxies not only ex and Toomre & Toomre (1972), among others, has led to growing evidence that gravitational interactions between neighbouring galaxies not only explain some of the most striking 'bridges' and 'tails' observed in disturbed gal itational interactions between neighbouring galaxies not only explain some of the
most striking 'bridges' and 'tails' observed in disturbed galaxy pairs, but also tend
to lead to galactic mergers that often trigger bursts most striking 'bridges' and 'tails' observed in disturbed galaxy pairs, but also tend
to lead to galactic mergers that often trigger bursts of star formation and clearly
represent important phases of galaxy building (Lars to lead to galactic mergers the
represent important phases of
1992; Kennicutt *et al.* 1998).
Before reviewing some of the present important phases of galaxy building (Larson 1990; Barnes & Hernquist 92; Kennicutt *et al.* 1998).
Before reviewing some of the evidence that suggests that interactions and mergers e.g. significant driver of galax

1992; Kennicutt *et al.* 1998).
Before reviewing some of the evidence that suggests that interactions and mergers
are a significant driver of galaxy evolution, it seems wise to agree on some terminology
and point out bias Before reviewing som
are a significant driver c
and point out biases. and point out biases.
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Figure 1. Neutral hydrogen distribution and kinematics of NGC 4038/4039. (Left) HI contour
lines (white) superimposed on an optical photograph. (Right) HI position–velocity plot, with Figure 1. Neutral hydrogen distribution and kinematics of NGC 4038/4039. (Left) HI contour
lines (white) superimposed on an optical photograph. (Right) HI position-velocity plot, with
declination along u-axis and line-ofŏ lines (white) superimposed on an optical photograph. (Right) HI position-velocity plot, with declination along y -axis and line-of-sight velocity along x-axis (from Hibbard 2000).

To be called a 'merger', a galaxy pair or single galaxy should at least show clear To be called a 'merger', a galaxy pair or single galaxy should at least show clear
morphological signatures of an advanced tidal interaction, such as significant dis-
tortions, major tails, and ripples or 'shells' (see Sch To be called a 'merger', a galaxy pair or single galaxy should at least show clear
morphological signatures of an advanced tidal interaction, such as significant dis-
tortions, major tails, and ripples or 'shells' (see Sch morphological signatures of an advanced tidal interaction, such as significant dis-
tortions, major tails, and ripples or 'shells' (see Schweizer (1998) for a review). A
stronger case for merging can usually be made when tortions, major tails, and ripples or 'shells' (see Schweizer (1998) for a review). A
stronger case for merging can usually be made when *kinematic* signatures are also
available, such as opposite tail motions, counter-rot available, such as opposite tail motions, counter-rotating parts, or tail material falling back onto a remnant. As figure 1 illustrates, much recent progress in this area is due available, such as opposite tail motions, counter-rotating parts, or tail material falling
back onto a remnant. As figure 1 illustrates, much recent progress in this area is due
to the ability of the upgraded *Very Large A* back onto a remnant. As figure 1 illustrates, much recent progress in this
to the ability of the upgraded *Very Large Array* to map the line-of-sight
neutral hydrogen (HI) in tidal features in great detail (Hibbard 2000).
 the ability of the upgraded *Very Large Array* to map the line-of-sight motions of utral hydrogen (HI) in tidal features in great detail (Hibbard 2000).
The main bias in studies of gravitational interactions has been towar

neutral hydrogen (HI) in tidal features in great detail (Hibbard 2000).
The main bias in studies of gravitational interactions has been towards major mergers, which involve two galaxies of nearly equal mass. Such mergers a tive and tend to lead to spectacular morphologies, whence they can be observed from ers, which involve two galaxies of nearly equal mass. Such mergers are highly destructive and tend to lead to spectacular morphologies, whence they can be observed from the local Universe out to redshifts of $z \approx 2$ and b tive and tend to lead to spectacular morphologies, whence they can be observed from
the local Universe out to redshifts of $z \approx 2$ and beyond. Minor mergers involving
galaxies with mass ratios of, say, $m/M = 0.1{\text -}0.5$, a the local Universe out to redshifts of $z \approx 2$ and beyond. Minor mergers involving galaxies with mass ratios of, say, $m/M = 0.1{\text -}0.5$, are less spectacular and often require verification via some kinematic signature (esp galaxies with mass ratios of, say, $m/M = 0.1$ –0.5, are less spectacular and often
require verification via some kinematic signature (especially in the remnant phase).
Hence, such interactions and mergers have been studied require verification via some kinematic signature (especially in the remnant phase).
Hence, such interactions and mergers have been studied mainly in nearby galaxies
and out to $z \lesssim 0.5$. Finally, although satellite acc Hence, such interactions and mergers have been studied mainly in nearby galaxies
and out to $z \lesssim 0.5$. Finally, although satellite accretions leading to mass increases of
a few per cent or less may be relatively frequen a few per cent or less may be relatively frequent, they are the most difficult to detect and have been studied only in the 'Local Group', and even there nearly exclusively a few per cent or less may be relatively frequent, they are the most difficult to detect
and have been studied only in the 'Local Group', and even there nearly exclusively
in our Milky Way Galaxy. Thus, our knowledge of gr and have been studied only in the '
in our Milky Way Galaxy. Thus, o
minor mergers is severely limited.
Because of its dissinative nature our Milky Way Galaxy. Thus, our knowledge of growth through accretions and
nor mergers is severely limited.
Because of its dissipative nature, gas plays a disproportionately large role in galaxy
ceractions. Even at the pre

minor mergers is severely limited.
Because of its dissipative nature, gas plays a disproportionately large role in galaxy
interactions. Even at the present epoch, the vast majority of galaxies contain signif-
icant amount Because of its dissipative nature, gas plays a disproportionately large role in galaxy interactions. Even at the present epoch, the vast majority of galaxies contain significant amounts of cold gas (Roberts $\&$ Haynes 19 interactions. Even at the present epoch, the vast majority of galaxies contain significant amounts of cold gas (Roberts & Haynes 1994). During tidal interactions and mergers this gas tends to be driven towards the centres icant amounts of cold gas (Roberts & Haynes 1994). During tidal interactions and
mergers this gas tends to be driven towards the centres of galaxies through gravita-
tional torques exerted on it by tidally induced *stella* mergers this gas tends to be driven towards the centres of galaxies through gravitational torques exerted on it by tidally induced *stellar* bars (see, for example, Barnes & Hernquist 1996). The ensuing shocks and energy d tional torques exerted on it by tidally induced *stellar* bars (see, for example, Barnes & Hernquist 1996). The ensuing shocks and energy dissipation allow the gas to get compressed, leading to intense bursts of star forma *Phil. Trans. R. Soc. Lond.* A (2000)

and the feeding of nuclear activity. Starbursts and active galactic nuclei in turn drive and the feeding of nuclear activity. Starbursts and active galactic nuclei in turn drive galactic winds and jets, which can have profound effects on the chemical evolution of galaxies (Heckman, this issue). and the feeding of nuclear activity. Sylandic winds and jets, which can
of galaxies (Heckman, this issue).
Some of these processes can now decreases the shorter profound effects on the chemical evolution
galaxies (Heckman, this issue).
Some of these processes can now be reproduced by modern N-body simulations
at include gas hydrodynamics. Barnes (1999) shows

of galaxies (Heckman, this issue).
Some of these processes can now be reproduced by modern N -body simulations
that include gas hydrodynamics. Barnes (1999) shows a beautiful sequence of two
gas-rich disc galaxies mergin Some of these processes can now be reproduced by modern N -body simulations
that include gas hydrodynamics. Barnes (1999) shows a beautiful sequence of two
gas-rich disc galaxies merging. Whereas their stars end up in a gas-rich disc galaxies merging. Whereas their stars end up in a three-dimensional pile
not unlike an elliptical galaxy with considerable fine structure, more than half of the gas-rich disc galaxies merging. Whereas their stars end up in a three-dimensional pile
not unlike an elliptical galaxy with considerable fine structure, more than half of the
cold gas from the input discs gets funnelled t not unlike an elliptical galaxy with considerable fine structure, more than half of the cold gas from the input discs gets funnelled to the centre of the remnant into a region only *ca*. 0.5 kpc in diameter, while the ini cold gas from the input discs gets funnelled to the centre of the remnant into a region
only ca. 0.5 kpc in diameter, while the initially warm gas $(T \approx 10^4 \text{ K})$ gets heated
to X-ray temperatures (ca. 10⁶ K) and forms only ca. 0.5 kpc in diameter, while the initially warm gas $(T \approx 10^4 \text{ K})$ gets heated
to X-ray temperatures $(ca.10^6 \text{ K})$ and forms a pressure-supported atmosphere with
similar dimensions to the stellar pile. The time-sc is galaxies dimensions to the stellar pile. The time-scale for this transformation from two disc galaxies to one merged remnant is remarkably short: about 1.5 rotation periods of the input discs, or, when scaled to component galaxies of Milky Way size, $ca.400$ Myr. two disc galax
periods of the
ca. 400 Myr.
The rapidit riods of the input discs, or, when scaled to component galaxies of Milky Way size,
100 Myr.
The rapidity of this equal-mass merger is due to strong dynamical friction. We
ould keep this in mind when trying to understand th

The rapidity of this equal-mass merger is due to strong dynamical friction. We should keep this in mind when trying to understand the formation of elliptical galaxies in dense environments. Claims have been made that cluster ellipticals formed in a should keep this in mind when trying to understand the formation of elliptical galaxies in dense environments. Claims have been made that cluster ellipticals formed in a rapid monolithic collapse because their present-day ies in dense environments. Claims have been made that cluster ellipticals formed in a
rapid monolithic collapse because their present-day colours are rather uniform. Yet,
experts agree that age differences of $\lesssim 3$ Gyr rapid monolithic collapse because their present-day colours are rather uniform. Yet,
experts agree that age differences of $\lesssim 3$ Gyr cannot be discerned from the broad-
band colours of galaxies 10–15 Gyr old. A time in experts agree that age differences of $\lesssim 3$ Gyr cannot be discerned from the broad-
band colours of galaxies 10–15 Gyr old. A time interval of 3 Gyr may seem short
when we struggle with logarithmic age estimates, yet i band colours of galaxies 10–15 Gyr old. A time interval of 3 Gyr may seem short
when we struggle with logarithmic age estimates, yet it is long when compared with
the merger time-scale. About eight major mergers of the kin when we struggle with logarithmic age estimates, yet it is long when compared with
the merger time-scale. About eight major mergers of the kind simulated by Barnes
(1999) could take place one after another during this time the merger time-scale. About eight major mergers of the kind simulated by Barnes (1999) could take place one after another during this time-interval, and 12 Gyr later all their remnants would appear nearly the same colour (1999) could take place one after another during this time-interval, and 12 Gyr later all their remnants would appear nearly the same colour and age. Hence, claims about monolithic collapses and a single epoch of elliptic all their remnants would appear nearly the same colour and age. Hence, claims about monolithic collapses and a single epoch of elliptical formation are to be taken with a pinch of salt. There was time for many major merger the first few Gyr after the Big Bang, and most cluster ellipticals could have formed a pinch of salt. There was time for many major mergers of juvenile discs of the first few Gyr after the Big Bang, and most cluster ellipticals could have for through such mergers without us knowing it from their present-da e first few Gyr after the Big Bang, and most cluster ellipticals could have formed
rough such mergers without us knowing it from their present-day colours.
The following review of evidence for interactions being a driver o

through such mergers without us knowing it from their present-day colours.
The following review of evidence for interactions being a driver of galaxy evolution
begins with accretions in the 'Local Group', continues with mi The following review of evidence for interactions being a driver of galaxy evolution
begins with accretions in the 'Local Group', continues with minor mergers and the
damage they inflict on disc galaxies, moves on to major begins with accretions in the 'Local Group', continues with minor mergers and the damage they inflict on disc galaxies, moves on to major mergers forming ellipticals from wrecked discs, and ends with a brief description of damage they inflict on disc galaxies, mc
from wrecked discs, and ends with a brit
first glimpses of high-redshift mergers.

1-reasmnt mergers.
2. Interactions in the 'Local Group'

2. Interactions in the 'Local Group'
There are many signs of recent or ongoing gravitational interactions in the Local
Group including the warped discs of the Milky Way M31 and M33 the Magellanic There are many signs of recent or ongoing gravitational interactions in the Local
Group, including the warped discs of the Milky Way, M 31, and M 33, the Magellanic
Stream and the integral-sign distortion of NGC 205 compan There are many signs of recent or ongoing gravitational interactions in the Local Group, including the warped discs of the Milky Way, M 31, and M 33, the Magellanic Stream, and the integral-sign distortion of NGC 205, comp Group, including the warped discs of the Milky Way, M 31, and M 33, the Magellanic Stream, and the integral-sign distortion of NGC 205, companion to M 31. However, the details of these interactions are often difficult to e Stream, and the integral-sign distortion of NGC 205, companion to M 31. Howe
the details of these interactions are often difficult to establish, and the cumula
effect of interactions not directly leading to mergers remains e details of these interactions are often difficult to establish, and the cumulative
fect of interactions not directly leading to mergers remains largely unknown.
Fortunately, there is now—in the Milky Way—some good, detai

effect of interactions not directly leading to mergers remains largely unknown.
Fortunately, there is now—in the Milky Way—some good, detailed evidence for
interactions leading to accretions. Three pieces of evidence stand \bullet Fortunately, there is now—in the Milky Way—s
interactions leading to accretions. Three pieces of everliable among the many that have been claimed.
First and most impressive is the Sagittarius dwar teractions leading to accretions. Three pieces of evidence stand out as particularly
liable among the many that have been claimed.
First and most impressive is the Sagittarius dwarf galaxy, hidden from us behind
e Milky W

reliable among the many that have been claimed.
First and most impressive is the Sagittarius dwarf galaxy, hidden from us behind
the Milky Way bulge until its recent discovery by Ibata *et al.* (1994). Located at a
distanc First and most impressive is the Sagittarius dwarf galaxy, hidden from us behind
the Milky Way bulge until its recent discovery by Ibata *et al.* (1994). Located at a
distance of 16 kpc from the galactic centre, this dwar the Milky Way bulge until its recent discovery by Ibata *et al.* (1994). Located at a distance of 16 kpc from the galactic centre, this dwarf appears very elongated in a direction approximately perpendicular to the galacti direction approximately perpendicular to the galactic plane and is thought to move in
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a nearly polar orbit with current perigalactic and apogalactic distances of *ca*. 20 kpc
and *ca*. 60 kpc. respectively (Ibata & Lewis 1998). Although it may have started out a nearly polar orbit with current perigalactic and apogalactic distances of *ca*. 20 kpc
and *ca*. 60 kpc, respectively (Ibata & Lewis 1998). Although it may have started out
with a mass of as much as $10^{11} M_{\odot}$ or as *IATHEMATICAL,
'HYSICAL
k ENGINEERING
CIENCES* a nearly polar orbit with current perigalactic and apogalactic distances of *ca*. 20 kpc
and *ca*. 60 kpc, respectively (Ibata & Lewis 1998). Although it may have started out
with a mass of as much as $10^{11} M_{\odot}$ or as and ca. 60 kpc, respectively (Ibata & Lewis 1998). Although it may have started out
with a mass of as much as $10^{11} M_{\odot}$ or as little as ca. $10^9 M_{\odot}$ (Jiang & Binney 2000),
the dwarf is estimated to currently have the dwarf is estimated to currently have a mass of 2×10^8 – $10^9 M_{\odot}$ and an orbital period of ca 0.7–1 Gyr. It will probably disrupt completely over the next few orbits
and will then deliver its four globular clusters, one of which appears to be its nucleus
(see, for example, Da Costa & Armandroff 1995) and will then deliver its four globular clusters, one of which appears to be its nucleus

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d will then deliver its four globular clusters, one of which appears to be its nucleus
ee, for example, Da Costa & Armandroff 1995), to the halo of the Milky Way.
As Searle & Zinn (1978) conjectured, similar accretions of (see, for example, Da Costa & Armandroff 1995), to the halo of the Milky Way.
As Searle & Zinn (1978) conjectured, similar accretions of gas fragments and dwarfs
may have built this halo over a prolonged period. A second THE ROYAL
SOCIETY may have built this halo over a prolonged period. A second piece of evidence strongly supporting this view is the observed retrograde mean motion of certain subsystems supporting this view is the observed retrograde mean motion of certain subsystems
of globular clusters (Rodgers & Paltoglou 1984; Zinn 1993). How could a mono-
lithic collapse possibly have led to a 15% minority of slightl of globular clusters (Rodgers & Paltoglou 1984; Zinn 1993). How could a monoof globular clusters (Rodgers & Paltoglou 1984; Zinn 1993). How could a mono-
lithic collapse possibly have led to a 15% minority of slightly younger halo globulars
orbiting in the opposite sense from the majority of old lithic collapse possibly have led to a 15% minority of slightly younge
orbiting in the opposite sense from the majority of old globulars and
Accretions from different directions provide a natural explanation.
Most accretio orbiting in the opposite sense from the majority of old globulars and the disc itself?
Accretions from different directions provide a natural explanation.
Most accretions into the halo must have occurred in the first 25-30

Accretions from different directions provide a natural explanation.
Most accretions into the halo must have occurred in the first 25–30% of the age of
our Galaxy. Colours and inferred minimum ages of halo stars suggest tha Most accretions into the halo must have occurred in the first 25–30% of the age of
our Galaxy. Colours and inferred minimum ages of halo stars suggest that by 10 Gyr
ago such accretions had diminished to a trickle, and si our Galaxy. Colours and inferred minimum ages of halo stars suggest that by 10 Gyr ago such accretions had diminished to a trickle, and since then \lesssim 6 Sagittarius-like dwarfs could have been accreted (Unavane *et al.* ago such accretions had diminished to a trickle, and since then \lesssim 6 Sagittarius-like
dwarfs could have been accreted (Unavane *et al.* 1996). Hence, the ongoing accretion
of Sgr Dwarf is by now a relatively rare even varfs could have been accreted (Unavane *et al.* 1996). Hence, the ongoing accretion Sgr Dwarf is by now a relatively rare event.
However, a much more massive accretion may still lie in the future. This is sug-
sted by th

gested by the Magellanic Stream, the third piece of good evidence for a relatively strong interaction involving the Milky Way. This stream of HI extends over 120° gested by the Magellanic Stream, the third piece of good evidence for a relatively
strong interaction involving the Milky Way. This stream of HI extends over 120^o
in the sky, arching from the Magellanic Clouds through t strong interaction involving the Milky Way. This stream of HI extends over 120[°] in the sky, arching from the Magellanic Clouds through the South Galactic Pole to declination -30° , where it was first discovered (Diet to declination -30° , where it was first discovered (Dieter 1965; Mathewson *et al.* 1974). After a long and tortuous history of interpretations, modern models based on a past gravitational interaction between the Lar 1974). After a long and tortuous history of interpretations, modern models based on
a past gravitational interaction between the Large Magellanic Cloud–Small Magel-
lanic Cloud (LMC–SMC) system and the Milky Way are now re a past gravitational interaction between the Large Magellanic Cloud–Small Magellanic Cloud (LMC–SMC) system and the Milky Way are now reasonably successful at explaining the observed morphology of the stream, the high appr lanic Cloud (LMC–SMC) system and the Milky Way are now reasonably successful
at explaining the observed morphology of the stream, the high approach velocities
near its end, and the existence of a counter-stream on the oth at explaining the observed morphology of the stream, the high approach velocities
near its end, and the existence of a counter-stream on the other side of the Clouds
(see, for example, Gardiner & Noguchi 1996). According t near its end, and the existence of a counter-stream on the other side of the Clouds
(see, for example, Gardiner & Noguchi 1996). According to such models, the stream
and counter-stream represent a tidal tail and bridge dr (see, for example, Gardiner & Noguchi 1996). According to such models, the stream
and counter-stream represent a tidal tail and bridge drawn from the outer gas disc of
the SMC during a close passage to the Milky Way ca . and counter-stream represent a tidal tail and bridge drawn from the outer gas disc of
the SMC during a close passage to the Milky Way ca . $1-1.5$ Gyr ago. The prediction
is that the LMC-SMC binary will soon break up and the SMC during a close passage to the Milky Way *ca*. 1–1.5 Gyr ago. The
is that the LMC–SMC binary will soon break up and the more massive L
the first to merge with the Milky Way in *ca*. 7–8 Gyr (Lin *et al.* 1995).
The that the LMC-SMC binary will soon break up and the more massive LMC will be
e first to merge with the Milky Way in $ca. 7-8$ Gyr (Lin *et al.* 1995).
The LMC's mass is $ca. 4\%$ of that of the Milky Way, and its visual lumi

that the entire halo. Hence, this future accretion will be a major event, at least and the entire halo. Hence, this future accretion will be a major event, at least and μ The LMC's mass is $ca.4\%$ of that of the Milky Way, and its visual luminosity twice
that of the entire halo. Hence, this future accretion will be a major event, at least an
order of magnitude more massive and spectacular that of the entire halo. Hence, this future accretion will be a major event, at least an order of magnitude more massive and spectacular than the ongoing Sgr Dwarf accretion. Our descendants can expect significant halo gro order of magnitude more massive and spectacular than the ongoing Sgr Dwa
tion. Our descendants can expect significant halo growth, induced star for
and probably also a thickening of the present thin disc of the Milky Way.
 In. Our descendants can expect significant halo growth, induced star formation,
d probably also a thickening of the present thin disc of the Milky Way.
The main message from the above evidence is that—even though most accr

and probably also a thickening of the present thin disc of the Milky Way.
The main message from the above evidence is that—even though most accretions
in galaxies outside the Local Group are difficult to detect—they must h The main message from the above evidence is that—even though most accretions
in galaxies outside the Local Group are difficult to detect—they must have occurred
primarily early $(z \ge 2)$ and must have contributed significa in galaxies outside the Local Group are difficult to detect—they must have oprimarily early $(z \ge 2)$ and must have contributed significantly to the groperhaps even morphology of many disc galaxies similar to ours and M 31 perhaps even morphology of many disc galaxies similar to ours and M 31.
3. Damaged discs

3. Damaged discs
Between small accretions that barely affect disc galaxies and major mergers that
wreck discs there must be intermediate-strength interactions and minor mergers that Between small accretions that barely affect disc galaxies and major mergers that wreck discs there must be intermediate-strength interactions and minor mergers that *Phil. Trans. R. Soc. Lond.* A (2000)

Figure 2. Neutral hydrogen distribution of NGC 4650A, a S0 galaxy with a 'polar ring'. The HI
contours are superposed on an optical image of the galaxy (from Arnaboldi *et el.* 1997) ure 2. Neutral hydrogen distribution of NGC 4650A, a S0 galaxy with a 'polar ring'. The E contours are superposed on an optical image of the galaxy (from Arnaboldi *et al.* 1997).

contours are superposed on an optical image of the galaxy (from Arnaboldi *et al.* 1997).
Significantly affect discs yet do not destroy them. This immediately suggests three questions:

(1) How fragile are galaxy discs?

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- (2) Can bulges form through minor mergers?
- (3) If so, what fraction of bulges formed in this manner?

Early theoretical worries that accretions of even only a few per cent in mass might disrupt discs (Tóth & Ostriker 1992) have been dispelled by N-body simulations Early theoretical worries that accretions of even only a few per cent in mass might disrupt discs (Tóth & Ostriker 1992) have been dispelled by N-body simulations showing that model disc galaxies do survive minor mergers disrupt discs (Tóth & Ostriker 1992) have been dispelled by N-body simulations
showing that model disc galaxies do survive minor mergers with mass ratios of up
to $m/M \approx 0.3$, albeit tilted, warped, slightly thickened, and showing that model disc galaxies do survive minor mergers with mass ratios of up
to $m/M \approx 0.3$, albeit tilted, warped, slightly thickened, and often with an increased
bulge (Walker *et al.* 1996; Huang & Carlberg 1997; Ve to $m/M \approx 0.3$, albeit tilted, warped, slightly thickened, and often with an increased bulge (Walker *et al.* 1996; Huang & Carlberg 1997; Velázquez & White 1999). Hence, observations. galaxy discs are apparently less fragile than once thought, a fact also suggested by observations.
First, note that optical images are not always a reliable indicator of tidal inter-

betwations.
First, note that optical images are not always a reliable indicator of tidal inter-
actions, as the case of M 81 illustrates. Even when displayed at high contrast such
images of M 81 paint a rather serene scene First, note that optical images are not always a reliable indicator of tidal inter-
actions, as the case of M 81 illustrates. Even when displayed at high contrast such
images of M 81 paint a rather serene scene of a symmet actions, as the case of M81 illustrates. Even when displayed at high contrast such
images of M81 paint a rather serene scene of a symmetric grand-design spiral. Yet,
the HI distribution is highly asymmetric and dominated b images of M 81 paint a rather serene scene of a symmetric grand-design spiral. Yet,
the HI distribution is highly asymmetric and dominated by long tidal features whose
kinks reveal a strong triple interaction between M 81 the HI distribution is highly asymmetric and dominated by long tidal features whose
kinks reveal a strong triple interaction between M 81, NGC 3077, and M 82 (see Yun
et al. (1994), especially the cover page). M 81 has n Example interaction between M 81, NGC 3077, and M 82 (see Yun
 $\begin{bmatrix}et \ al. (1994),\end{bmatrix}$, especially the cover page). M 81 has not only survived this interaction,

but probably owes its beautiful spiral structure to it (To et al. (1994) , especially the cover page). M 81 has not only survived this interaction,

suggest that especially gas-rich discs may well survive minor mergers occurring from Second, S0 galaxies with polar rings of gas, dust, and young stars increasingly suggest that especially gas-rich discs may well survive minor mergers occurring from near-polar orbits. Such S0 galaxies were long thought to suggest that especially gas-rich discs may well survive minor mergers occurring from
near-polar orbits. Such S0 galaxies were long thought to have accreted their ring
gas during a fly-by or minor merger (see, for example, gas during a fly-by or minor merger (see, for example, Toomre 1977; Schweizer *et al.* 1983). Yet, many of the S0 bodies feature post-starburst spectra, and HI observations show that the gas contents of the polar rings ten 1983). Yet, many of the S0 bodies feature post-starburst spectra, and HI observations
show that the gas contents of the polar rings tend to be large and typical of full-
grown late-type spirals (Richter *et al.* 1994; Res show that the gas contents of the polar rings tend to be large and typical of full-
grown late-type spirals (Richter *et al.* 1994; Reshetnikov & Combes 1994; Arnaboldi
et al. 1997), as illustrated in figure 2. Thus it a grown late-type spirals (Richter *et al.* 1994; Reshetnikov & Combes 1994; Arnaboldi *et al.* 1997), as illustrated in figure 2. Thus it appears that the central S0 galaxies may be remnants of disc companions having falle *Phil. Trans. R. Soc. Lond.* A (2000)

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2068 $F. Schweizer$
rings—nearly over their poles (Bekki 1998). If so, these central S0 bodies represent
failed bulges. The crucial point is that two disc systems of not too dissimilar mass rings—nearly over their poles (Bekki 1998). If so, these central S0 bodies represent failed bulges. The crucial point is that two disc systems of not too dissimilar mass
apparently can survive a merger and—helped by gaseou **IATHEMATICAL,
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CIENCES** failed bulges. The crucial point is that two disc systems of not too dissimilar mass apparently *can* survive a merger and—helped by gaseous dissipation—retain their disc identity. apparently can survive a merger and—helped by gaseous dissipation—retain their

Disc galaxies survive even non-polar minor mergers, as evidenced by a multitude of kinematic signatures. For example, the Sab galaxy NGC 4826 has a gas disc consisting of two nested counter-rotating parts, each of nearly equal mass (Braun *et al.*) Disc galaxies survive even non-polar minor mergers, as evidenced by a multitude of kinematic signatures. For example, the Sab galaxy NGC 4826 has a gas disc consisting of two nested counter-rotating parts, each of nearly e sisting of two nested counter-rotating parts, each of nearly equal mass (Braun *et al.* 1994). The inner component rotates like the stellar disc and bulge, while the outer component counter-rotates (Rubin 1994). The two c 1994). The inner component rotates like the stellar disc and bulge, while the outer component counter-rotates (Rubin 1994). The two comparable gas masses suggest that the intruder galaxy was not a mere dwarf a few per cent component counter-rotates (Rubin 1994). The t
that the intruder galaxy was not a mere dwarf a
massive companion leading to a minor merger.
Whereas similar kinematic signatures are rare as the intruder galaxy was not a mere dwarf a few per cent in mass, but a more
assive companion leading to a minor merger.
Whereas similar kinematic signatures are rare among Sb galaxies, they are more
couent among Sa gala

massive companion leading to a minor merger.
Whereas similar kinematic signatures are rare among Sb galaxies, they are more
frequent among Sa galaxies and nearly the norm among S0 galaxies. From the statis-
tics of counter Whereas similar kinematic signatures are rare among Sb galaxies, they are more
frequent among Sa galaxies and nearly the norm among S0 galaxies. From the statis-
tics of counter-rotating, skewedly rotating, and corotating frequent among Sa galaxies and nearly the norm among S0 galaxies. From the statistics of counter-rotating, skewedly rotating, and corotating ionized-gas discs one can conclude that at least $40-70\%$ of all S0 galaxies ex tics of counter-rotating, skewedly rotating, and corotating ionized-gas discs one can
conclude that at least 40–70% of all S0 galaxies experienced minor mergers (Bertola
et al. 1992). The fact that the frequency of kinem conclude that at least $40-70\%$ of all S0 galaxies experienced minor mergers (Bertola *et al.* 1992). The fact that the frequency of kinematic signatures of past mergers increases with bulge size strongly suggests that a mergers. creases with bulge size strongly suggests that at least major bulges formed through
ergers.
Another powerful merger signature correlating with morphological type is the sub-
pulations of stars counter-rotating in disc gala

Another powerful merger signature correlating with morphological type is the sub-
populations of stars counter-rotating in disc galaxies of types S0 to Sb. A well-known example is the E/S0 galaxy NGC 4550, in which half of the disc *stars* rotate one way populations of stars counter-rotating in disc galaxies of types S0 to Sb. A well-known
example is the E/S0 galaxy NGC 4550, in which half of the disc *stars* rotate one way
and the other half rotate the opposite way (Rubin example is the $E/S0$ galaxy NGC 4550, in which half of the disc *stars* rotate one way
and the other half rotate the opposite way (Rubin *et al.* 1992). In several Sa and Sb
galaxies the split between normal- and counterand the other half rotate the opposite way (Rubin *et al.* 1992). In several Sa and Sb galaxies the split between normal- and counter-rotating disc stars is of the order of $70/30\%$. Finally, a bulge rotating at right an galaxies the split between normal- and counter-rotating disc stars is of the order of $70/30\%$. Finally, a bulge rotating at right angles to the stellar disc has been observed in the Sa galaxy NGC 4698 (Bertola *et al.* 1999), and bulges counter-rotating to the discs are seen in the Sb galaxies NGC 7331 and NGC 2841 (Prada *et al.* 1996, and F. Prada, personal communication; also see Bottema 199 discs are seen in the Sb galaxies NGC 7331 and NGC 2841 (Prada *et al.* 1996, and discs are seen in the Sb galaxies NGC 7331 and NGC 2841 (Prada *et al.* 1996, and F. Prada, personal communication; also see Bottema 1999). N-body simulations suggest that minor and not-so-minor mergers can indeed produce F. Prada, personal communication; also see Botten
suggest that minor and not-so-minor mergers can inde
(Thakar & Ryden 1998; Balcells & González 1998).
In short, galactic discs—especially those rich in gas ggest that minor and not-so-minor mergers can indeed produce such odd rotations

'hakar & Ryden 1998; Balcells & González 1998).

In short, galactic discs—especially those rich in gas—appear not nearly as fragile

thought

(Thakar & Ryden 1998; Balcells & González 1998).
In short, galactic discs—especially those rich in gas—appear not nearly as fragile
as thought only a few years ago. Both observations and numerical simulations sug-
gest th In short, galactic discs—especially those rich in gas—appear not nearly as fragile
as thought only a few years ago. Both observations and numerical simulations sug-
gest that minor mergers do occur in disc galaxies and con as thought only a few years ago. Both observations and numerical simulations suggest that minor mergers do occur in disc galaxies and contribute to bulge building.
However, we do not know the exact fraction of bulges that gest that minor mergers do occur in disc galaxies and contribute to bulge building.
However, we do not know the exact fraction of bulges that were built in this manner.
Also unclear is how unique or varied the possible pat However, we do not know the exact fraction of bulges that were built in this manner.
Also unclear is how unique or varied the possible paths to, say, a present-day Sb
galaxy are. Which formed first: the disc or the bulge? Also unclear is how unique or varied t
galaxy are. Which formed first: the disc
episodically, perhaps even by turns? episodically, perhaps even by turns?
4. Ellipticals from wrecked discs

4. Ellipticals from wrecked discs
The notion that galaxy collisions are highly inelastic (Alladin 1965) and lead—via
dynamical friction and orbital decay—to mergers (Toomre & Toomre 1972) is now The notion that galaxy collisions are highly inelastic (Alladin 1965) and lead—via
dynamical friction and orbital decay—to mergers (Toomre & Toomre 1972) is now
well supported by both N-body simulations and observations (s \bigcirc dynamical friction and orbital decay—to mergers (Toomre & Toomre 1972) is now well supported by both N-body simulations and observations (see, for example, dynamical friction and orbital decay—to mergers (Toomre & Toomre 1972) is now
well supported by both N-body simulations and observations (see, for example,
Barnes 1998). Major mergers clearly do wreck discs and can form g well supported by both *N*-body simulations and observations (see, for example, Barnes 1998). Major mergers clearly do wreck discs and can form giant ellipticals, as first proposed by Toomre & Toomre (1972). What remains Barnes 1998). Major mergers clearly do wreck discs and can form giant ellipticals, as
first proposed by Toomre & Toomre (1972). What remains controversial is whether
most ellipticals formed in this manner, and whether th first proposed by Toomre & Toomre (1972). What remains controversial is whether *most* ellipticals formed in this manner, and whether those in clusters formed in a systematically different way from those in the field. As most ellipticals formed in this manner, and whether those in clusters formed in a
systematically different way from those in the field. As described below, there is
growing evidence that most giant ellipticals did indeed f systematically different way from those in the field. As described bely
prowing evidence that most giant ellipticals did indeed form through ma
and that this occurred earlier on average in clusters than in the field. *Phil. Trans. R. Soc. Lond.* A (2000)

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Figure 3. Two recent merger remnants, NGC 3921 (*a*) and NGC 7252 (*b*), with properties 3. Two recent merger remnants, NGC 3921 (a) and NGC 7252 (b) , with prop marking them as present-day proto-ellipticals (from Schweizer 1996, 1982).

marking them as present-day proto-ellipticals (from Schweizer 1996, 1982).
First, the evidence is strong that remnants of *recent* equal-disc mergers are present-First, the evidence is strong that remnants of *recent* equal-disc mergers are present-
day proto-ellipticals. The main theoretical advance has been the inclusion of dark-
matter halos and gas in the N-body simulations le First, the evidence is strong that remnants of *recent* equal-disc mergers are present-
day proto-ellipticals. The main theoretical advance has been the inclusion of dark-
matter halos and gas in the N-body simulations, l day proto-ellipticals. The main theoretical advance has been the inclusion of dark-
matter halos and gas in the N-body simulations, leading to efficient mechanisms for
outward angular-momentum transport and central densit matter halos and gas in the N-body simulations, leading to efficient mechanisms for
outward angular-momentum transport and central density increases (Barnes 1988;
Barnes & Hernquist 1996). The model remnants are generally outward angular-momentum transport and central density increases (Barnes 1988;
Barnes & Hernquist 1996). The model remnants are generally triaxial, violently but
incompletely relaxed, and lack rotational support. Their pro Barnes & Hernquist 1996). The model remnants are generally triaxial, violently but
incompletely relaxed, and lack rotational support. Their projected isophotes, which
are determined mainly by the inclinations of the progen incompletely relaxed, and lack rotational support. Their projected isophotes, which
are determined mainly by the inclinations of the progenitor discs and the viewing
geometry, can range from boxy through boxy-and-discy to are determined mainly by the inclinations of the progenitor discs and the viewing
geometry, can range from boxy through boxy-and-discy to rather strongly discy, as
observed in real E and E/S0 galaxies (Barnes 1992; Heyl *e* geometry, can range from boxy through boxy-and-discy to rather strongly discy, as
observed in real E and E/S0 galaxies (Barnes 1992; Heyl *et al.* 1994). Observation-
ally, recent merger remnants such as NGC 3921 and NGC observed in real E and E/S0 galaxies (Barnes 1992; Heyl *et al.* 1994). Observationally, recent merger remnants such as NGC 3921 and NGC 7252 (figure 3) feature pairs of tidal tails but single main bodies with relaxed, r $1/4$ _{-tv} ally, recent merger remnants such as NGC 3921 and NGC 7252 (figure 3) feature
pairs of tidal tails but single main bodies with relaxed, $r^{1/4}$ -type light distributions
(Schweizer 1982, 1996; Stanford & Bushouse 1991). T pairs of tidal tails but single main bodies with relaxed, $r^{1/4}$ -type light distributions (Schweizer 1982, 1996; Stanford & Bushouse 1991). Their power-law cores, central luminosity densities, velocity dispersions, and (Schweizer 1982, 1996; Stanford & Bushouse 1991). Their power-law cores, central
luminosity densities, velocity dispersions, and radial colour gradients are typical of
giant ellipticals (Lake & Dressler 1986; Doyon *et al.* luminosity densities, velocity dispersions, and radial colour gradients are typical of
giant ellipticals (Lake & Dressler 1986; Doyon *et al.* 1994). Major starbursts, reflected
in the integrated-light spectra and in majo giant ellipticals (Lake & Dressler 1986; Doyon *et al.* 1994). Major starbursts, reflected
in the integrated-light spectra and in major populations of young star clusters, seem
to have converted 10–30% of the visible mass in the integrated-light spectra and in major populations of young star clusters, seem
to have converted 10–30% of the visible mass into stars and have nearly doubled the
number of globular clusters. Therefore, in all thei to have converted 10–30% of the visible mass
number of globular clusters. Therefore, in all
appear to be \lesssim 1 Gyr old proto-ellipticals.
Second recent remnants of disc-disc merger number of globular clusters. Therefore, in all their observed properties such remnants appear to be \lesssim 1 Gyr old proto-ellipticals.
Second, recent remnants of disc-disc mergers display several phenomena that con-

appear to be \lesssim 1 Gyr old proto-ellipticals.
Second, recent remnants of disc-disc mergers display several phenomena that con-
nect them also to much older ellipticals. Foremost among these phenomena is the
return of ti Second, recent remnants of disc-disc mergers display several phenomena that connect them also to much older ellipticals. Foremost among these phenomena is the return of tidally ejected material. Model simulations including nect them also to much older ellipticals. Foremost among these phenomena is the return of tidally ejected material. Model simulations including the effects of massive dark halos predict that most of the matter ejected by t The return of tidally ejected material. Model simulations including the effects of massive dark halos predict that most of the matter ejected by two merging discs into the list remains bound and must eventually fall back o sive dark halos predict that most of the matter ejected by two merging discs into
tails remains bound and must eventually fall back onto the merger remnant (Barnes
1988). This infall is observed in the HI gas near the bas tails remains bound and must eventually fall back onto the merger remnant (Barnes 1988). This infall is observed in the HI gas near the base of the tails of NGC 7252 and NGC 3921 (Hibbard *et al.* 1994; Hibbard & van Gorko 1988). This infall is observed in the HI gas near the base of the tails of NGC 7252
and NGC 3921 (Hibbard *et al.* 1994; Hibbard & van Gorkom 1996) and is presum-
ably shared by the stars. Interestingly, HI absorption in and NGC 3921 (Hibbard *et al.* 1994; Hibbard $\&$ van Gorkom 1996) and is presumably shared by the stars. Interestingly, HI absorption in radio ellipticals invariably indicates gas infall (van Gorkom *et al.* 1989). Infal ably shared by the stars. Interestingly, HI absorption in radio ellipticals invariably
indicates gas infall (van Gorkom *et al.* 1989). Infalling stars also yield a natural
explanation for many of the faint ripples ('shel indicates gas infall (van Gorkom *et al.* 1989). Infalling stars also yield a natural explanation for many of the faint ripples ('shells') and plumes observed in elliptical galaxies. As dynamically cold streams of stars f explanation for many of the faint ripples ('shells') and plumes observed in elliptical galaxies. As dynamically cold streams of stars fall back into the remnants, they wrap around the centre and form sharp-edged features cal galaxies. As dynamically cold streams of stars fall back into the remnants, they wrap around the centre and form sharp-edged features at their turnaround points (Hernquist & Spergel 1992; Hibbard & Mihos 1995). The hi (Hernquist & Spergel 1992; Hibbard & Mihos 1995). The high percentage $(ca. 70\%)$
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position along slit (")
Figure 4. Oddly rotating cores in two elliptical galaxies. Mean stellar velocities are shown as a
function of position along major axes. Note counter-rotating core of NGC 3608 and corotating Figure 4. Oddly rotating cores in two elliptical galaxies. Mean stellar velocities are shown as a function of position along major axes. Note counter-rotating core of NGC 3608 and corotating, but kinematically distinct cor function of position along major axes. Note counter-rotating core of NGC 3608 and corotating, but kinematically distinct core of NGC 4494 (Jedrzejewski $\&$ Schechter 1988).

of field ellipticals featuring such fine structure (Schweizer $\&$ Seitzer 1992) and the of field ellipticals featuring such fine structure (Schweizer & Seitzer 1992) and the considerable amounts of material indicated by integrated photometry (Prieur 1990) suggest that most of the observed fine structure cann of field ellipticals featuring such fine structure (Schweizer & Seitzer 1992) and the considerable amounts of material indicated by integrated photometry (Prieur 1990) suggest that most of the observed fine structure cann considerable amounts of material indicated by integrated photometry (Prieur 1990)
suggest that most of the observed fine structure cannot be due to mere dwarf galax-
ies falling in. Instead, such structure is much more lik suggest that most of the observed fine structure cannot be
ies falling in. Instead, such structure is much more likely t
major mergers that formed most, or even all, ellipticals.
Third various unexpected kinematic signatur ies falling in. Instead, such structure is much more likely to be the signature of past major mergers that formed most, or even all, ellipticals.
Third, various unexpected kinematic signatures in giant ellipticals also poi

**MATHEMATICAL,
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SCIENCES** major mergers that formed most, or even all, ellipticals.
Third, various unexpected kinematic signatures in giant ellipticals also point to-
wards past mergers of gas-rich discs. About a quarter of all ellipticals show odd Third, various unexpected kinematic signatures in giant ellipticals also point to-
wards past mergers of gas-rich discs. About a quarter of all ellipticals show oddly
rotating cores, some rotating in the opposite sense of wards past mergers of gas-rich discs. About a quarter of all ellipticals show oddly rotating cores, some rotating in the opposite sense of the main body, others at right angles, and still others in the same sense but much rotating cores, some rotating in the opposite sense of the main body, others at right
angles, and still others in the same sense but much faster (figure 4). When studied in
detail, such cores appear to be small discs $(r \approx$ angles, and still others in the same sense but much faster (figure 4). When studied in detail, such cores appear to be small discs $(r \approx 0.2-3 \text{ kpc})$ indicative of gaseous dissipation (see, for example, Bender 1996; Mehler detail, such cores appear to be small discs $(r \approx 0.2{\text -}3 \text{ kpc})$ indicative of gaseous dissipation (see, for example, Bender 1996; Mehlert *et al.* 1998). A similar central disc violently forming stars and probably fed by sipation (see, for example, Bender 1996; Mehlert *et al.* 1998). A similar central disc
violently forming stars and probably fed by gas returning from the tails is observed
in the merger remnant NGC 7252 (Wang *et al.* 199 violently forming stars and probably fed by gas returning from the tails is observed
in the merger remnant NGC 7252 (Wang *et al.* 1992; Whitmore *et al.* 1993). Model
simulations of disc mergers reproduce such odd core r simulations of disc mergers reproduce such odd core rotations quite naturally (Hern-
quist $\&$ Barnes 1991). The existence of distinct kinematic subsystems then argues simulations of disc mergers reproduce such odd core rotations quite naturally (Hern-
quist & Barnes 1991). The existence of distinct kinematic subsystems then argues
against ellipticals having assembled from many gaseous quist & Barnes 1991). The existence of distinct kinematic subsystems then argues
against ellipticals having assembled from many gaseous fragments and in favour of
two input discs. Exactly the same message is conveyed by ellipticals having assembled from many gaseous fragments and in favour of *two* input discs. Exactly the same message is conveyed by the growing number of ellipticals that—like, for example, NGC 5128 (Schiminovich *et al. two* input discs. Exactly the same message is conveyed by the growing number of ellipticals that—like, for example, NGC 5128 (Schiminovich *et al.* 1994)—possess *two*, often nearly orthogonally rotating, HI discs. Nearly ellipticals that—like, for example, NGC 5128 (Schiminovich *et al.* 1994)—possess *two*, often nearly orthogonally rotating, HI discs. Nearly three dozen ellipticals are now known to feature often fragmentary outer gas di two, often nearly orthogonally rotating, HI discs. Nearly three dozen ellipticals are
now known to feature often fragmentary outer gas discs or rings whose kinematics
appears decoupled from that of the main body (J. H. van mow known to feature often fragmentary outer gas discs or rings whose kinematics
appears decoupled from that of the main body (J. H. van Gorkom, personal com-
munication). Given that the gaseous tails of the remnant NGC 72 appears decoupled from that of the main body (J. H. van Gorkom, personal com-
munication). Given that the gaseous tails of the remnant NGC 7252 lie in mutually
inclined planes, there is strong reason to suspect that these munication). Given that the gaseous tails of the remnant NGC 7252 lie in mutually inclined planes, there is strong reason to suspect that these much older ellipticals acquired their outer gas through disc-disc mergers as w

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Fourth, yet another connection between disc mergers and elliptical galaxies is provided by globular star clusters. Although in nearby galaxies most such clusters appear to be very old and seem to have originated in the ear Fourth, yet another connection between disc mergers and elliptical galaxies is provided by globular star clusters. Although in nearby galaxies most such clusters appear to be very old and seem to have originated in the ear to be very old and seem to have originated in the earliest days of galaxy formation, young globulars have recently been found to form by the hundreds in the vehe-
ment starbursts induced by major mergers. Mergers like 'The young globulars have recently been found to form by the hundreds in the veheyoung globulars have recently been found to form by the hundreds in the vehe-
ment starbursts induced by major mergers. Mergers like 'The Antennae', NGC 3921,
and NGC 7252 can apparently produce nearly as many young globul ment starbursts induced by major mergers. Mergers like 'The Antennae', NGC 3921,
and NGC 7252 can apparently produce nearly as many young globular clusters as
the combined number of old globulars in the component discs, t and NGC 7252 can apparently produce nearly as many young globular clusters as
the combined number of old globulars in the component discs, thus approximately
doubling the number of clusters in the process (Miller *et al.* the combined number of old globulars in the component discs, thus approximately doubling the number of clusters in the process (Miller *et al.* 1997; Ashman & Zepf 1998). First spectroscopic evidence shows that, as one wo doubling the number of clusters in the process (Miller *et al.* 1997; Ashman & Zepf 1998). First spectroscopic evidence shows that, as one would expect, the young globulars have much higher heavy-element abundances than t 1998). First spectroscopic evidence shows that, as one would expect, the young globulars have much higher heavy-element abundances than the old ones, being of solar 'metallicity' in the case of NGC 7252 (Schweizer $\&$ Se in 'metallicity' in the case of NGC 7252 (Schweizer & Seitzer 1998). If major mergers \Box formed most ellipticals, one would therefore expect to find bimodal abundance dis-'metallicity' in the case of NGC 7252 (Schweizer & Seitzer 1998). If major mergers
formed most ellipticals, one would therefore expect to find bimodal abundance dis-
tributions among their globular-cluster populations (As formed most ellipticals, one would therefore expect to find bimodal abundance dis-
tributions among their globular-cluster populations (Ashman & Zepf 1992). This is
exactly what has been discovered during the past few year tributions among their globular-cluster populations (Ashman & Zepf 1992). This is
exactly what has been discovered during the past few years. Hubble Space Telescope
observations show that at least half of all giant ellipt exactly what has been discovered during the past few years. Hubble Space Telescope
observations show that at least half of all giant ellipticals feature bimodal cluster
distributions (Gebhardt & Kissler-Patig 1999; Kundu 1 distributions (Gebhardt & Kissler-Patig 1999; Kundu 1999). The ratio of second-to distributions (Gebhardt & Kissler-Patig 1999; Kundu 1999). The ratio of second- to
first-generation clusters seems to typically range between 0.5 and 1, and the second-
generation, metal-rich clusters tend to be more conce

Fourth, yet another connection between disc mergers and elliptical galaxies is pro-

 $\frac{1}{2}$ their host galaxies, as the merger hypothesis predicted.
Bimodal globular-cluster systems, oddly rotating cores, ripples and plumes, and neration, metal-rich clusters tend to be more concentrated towards the centres of
eir host galaxies, as the merger hypothesis predicted.
Bimodal globular-cluster systems, oddly rotating cores, ripples and plumes, and
st ou their host galaxies, as the merger hypothesis predicted.
Bimodal globular-cluster systems, oddly rotating cores, ripples and plumes, and
fast outer-halo rotation (Bridges 1999) occur not only in field ellipticals, but als Bimodal globular-cluster systems, oddly rotating cores, ripples and plumes, and fast outer-halo rotation (Bridges 1999) occur not only in field ellipticals, but also in cluster ellipticals, indicating that giant elliptical fast outer-halo rotation (Bridges 1
cluster ellipticals, indicating that g
both in the field *and* in clusters.
Merging galaxies and recent rem cluster ellipticals, indicating that giant ellipticals formed via major disc-disc mergers
both in the field *and* in clusters.
Merging galaxies and recent remnants show that disc wrecking is an ongoing pro-

Merging galaxies and recent remnants show that disc wrecking is an ongoing process. If the wrecks are mainly ellipticals, the latter's ages should vary widely. Measured UBV colours and spectral line-strength indices sugg cess. If the wrecks are mainly ellipticals, the latter's ages should vary widely. Meacess. If the wrecks are mainly ellipticals, the latter's ages should vary widely. Measured *UBV* colours and spectral line-strength indices suggest that this is indeed the case, with ages of field ellipticals ranging betw sured *UBV* colours and spectral line-strength indices suggest that this is indeed the case, with ages of field ellipticals ranging between *ca*. 2 Gyr and 12 Gyr (Schweizer & Seitzer 1992; González 1993; Faber *et al*. 19 case, with ages of field ellipticals ranging between $ca.2 \text{ Gyr}$ and 12 Gyr (Schweizer & Seitzer 1992; González 1993; Faber *et al.* 1995; Davies 1996; Trager *et al.* 2000). In cluster ellipticals, the colours and line s YSICAL
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IENCES & Seitzer 1992; González 1993; Faber *et al.* 1995; Davies 1996; Trager *et al.* 2000).
In cluster ellipticals, the colours and line strengths vary less and the inferred ages
are more uniformly old (De Carvalho & Djorgovs In cluster ellipticals, the colours and line strengths vary less and the inferred ages
are more uniformly old (De Carvalho & Djorgovski 1992), especially near the cluster
centres (Guzmán *et al.* 1992). These observations are more uniformly old (De Carvalho & Djorgovski 1992), especially near the cluster
centres (Guzmán *et al.* 1992). These observations all agree with the notion that, on
average, major mergers occurred earliest in high-de centres (Guzmán *et al.* 1992). These observations all agree with the notion that, on average, major mergers occurred earliest in high-density regions now at the centres of rich clusters, significantly later in cluster out average, major mergers occurred earliest in high-density regions now at the centres of rich clusters, significantly later in cluster outskirts where galaxies are still falling in, and at the slowest rate in the field.

 $\overline{}$ 5. High-redshift interactions
 $\overline{}$ Observational evidence that interactions and mergers were more frequent in the past 5. High-redshift interactions
Observational evidence that interactions and mergers were more frequent in the past
has trickled in since the late 1970s and has grown more rapidly since the late-1993 Observational evidence that interactions and mergers were more frequent in the past
has trickled in since the late 1970s and has grown more rapidly since the late-1993
repair of the Hubble Space Telescope. In general this Observational evidence that interactions and mergers were more frequent in the past
has trickled in since the late 1970s and has grown more rapidly since the late-1993
repair of the Hubble Space Telescope. In general this has trickled in since the late 1970s and has grown more rapidly since the late-1993
repair of the Hubble Space Telescope. In general this evidence agrees with expec-
tations based on numerical simulations of hierarchical c repair of the Hubble Space Telescope. In general this evidence agrees with expectations based on numerical simulations of hierarchical clustering in an expanding Universe dominated by dissipationless dark matter. However, tations based on numerical simulations of hierarchical clustering in an expanding
Universe dominated by dissipationless dark matter. However, quantitative observa-
tions of high-z interactions remain difficult to obtain. Universe dominated by dissipationless dark matter. However, quantitative observa-
tions of high-z interactions remain difficult to obtain. As we study objects from
 $z \approx 0.3$ to *ca*. 1.2, morphological details and kinemat tions of high-z interactions remain difficult to obtain. As we study objects from $z \approx 0.3$ to ca. 1.2, morphological details and kinematic signatures fade, and we are reduced to judging gross morphologies from a few pixe pairs. duced to judging gross morphologies from a few pixels or simply counting galaxy
irs.
Quasars yielded some of the earliest evidence for interactions at higher redshifts
 > 0.2). When near enough for details to be visible,

pairs.
Quasars yielded some of the earliest evidence for interactions at higher redshifts $(z \gtrsim 0.2)$. When near enough for details to be visible, they are often seen to occur $(z \gtrsim 0.2)$. When near enough for details to be visible, they are often seen to occur
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Figure 5. Galaxy interactions and mergers in Hercules cluster. Strongly interacting pair near
lower left corner shows giant diffuse tails. Photograph courtesy of Alan Dressler $\,$ 5. Galaxy interactions and mergers in Hercules cluster. Strongly interacting pair lower left corner shows giant diffuse tails. Photograph courtesy of Alan Dressler.

in host galaxies that either have close companions or are involved in major mergers in host galaxies that either have close companions or are involved in major mergers (Stockton 1990; Bahcall *et al.* 1997). The quasar OX 169, for example, features at least one tidal tail (probably a pair) and shows a va in host galaxies that either have close companions or are involved in major mergers (Stockton 1990; Bahcall *et al.* 1997). The quasar OX 169, for example, features at least one tidal tail (probably a pair) and shows a va (Stockton 1990; Bahcall *et al.* 1997). The quasar OX 169, for least one tidal tail (probably a pair) and shows a variable H indicative of *two* active nuclei (Stockton & Farnham 1991). Of special interest is the emerging least one tidal tail (probably a pair) and shows a variable $H\beta$ emission-line profile indicative of *two* active nuclei (Stockton & Farnham 1991).
Of special interest is the emerging connection between quasars and infra

indicative of *two* active nuclei (Stockton & Farnham 1991).
Of special interest is the emerging connection between quasars and infrared-luminous galaxies. At bolometric luminosities above $10^{12}L_{\odot}$ the so-called ult Of special interest is the emerging connection between quasars and infrared-luminous galaxies. At bolometric luminosities above $10^{12}L_{\odot}$ the so-called ultraluminous infrared galaxies (ULIG) become the dominant popul nous galaxies. At bolometric luminosities above $10^{12}L_{\odot}$ the so-called ultraluminous
infrared galaxies (ULIG) become the dominant population in the local Universe and
are 1.5–2 times as numerous as optically selecte infrared galaxies (ULIG) become the dominant population in the local Universe and
are 1.5–2 times as numerous as optically selected quasars. When ordered by increas-
ing far-infrared colour temperature, ULIGs and quasars s are 1.5–2 times as numerous as optically selected quasars. When ordered by increasing far-infrared colour temperature, ULIGs and quasars seem to form an evolution-
ary sequence: ULIGs with low colour temperature are starbu ing far-infrared colour temperature, ULIGs and quasars seem to form an evolution-
ary sequence: ULIGs with low colour temperature are starbursting disc mergers with
well-separated components, warm ULIGs appear to be just c ary sequence: ULIGs with low colour temperature are starbursting disc mergers with
well-separated components, warm ULIGs appear to be just completing their merging
into one object, and the 'hot', optically visible quasars well-separated components, warm ULIGs appear to be just completing their merging
into one object, and the 'hot', optically visible quasars shine in peculiar ellipticals
that resemble nearby merger remnants (Sanders *et al.* into one object, and the 'hot', optically visible quasars shine in peculiar ellipticals
that resemble nearby merger remnants (Sanders *et al.* 1988, 1999). Nuclear sepa-
rations and merger velocities indicate that the ULIG that resemble nearby merger remnants (Sanders *et al.* 1988, 1999). Nuclear separations and merger velocities indicate that the ULIG phase lasts ca 200–400 Myr.
Hence, extreme starbursts occurring while the nuclei merge rations and merger velocities indicate that the ULIG phase lasts ca. 200–400 Myr.
Hence, extreme starbursts occurring while the nuclei merge and nuclear feeding fren-
zies climaxing in a quasar phase appear to be natural Hence, extreme starbursts occurring while the nuclei merge and nuclear feeding frenzies climaxing in a quasar phase appear to be natural by-products of elliptical formation through mergers. The peak quasar activity observ zies climaxing in a quasar phase appear to be natural by-product
mation through mergers. The peak quasar activity observed around
mark the culmination of major mergers and elliptical formation.
Beyond $z \approx 2$ we have prec mation through mergers. The peak quasar activity observed around $z \approx 2$ may, then, mark the culmination of major mergers and elliptical formation.
Beyond $z \approx 2$ we have precious little *direct* evidence of interactions

mark the culmination of major mergers and elliptical formation.
Beyond $z \approx 2$ we have precious little *direct* evidence of interactions and merging.
The radio galaxy MCR 0406-244 at $z = 2.44$ may be one of the highest re Beyond $z \approx 2$ we have precious little *direct* evidence of interactions and merging.
The radio galaxy MCR 0406-244 at $z = 2.44$ may be one of the highest redshift
mergers for which there is some detailed structural infor The radio galaxy MCR 0406-244 at $z = 2.44$ may be one of the highest redshift mergers for which there is some detailed structural information. Deep optical Hubble Space Telescope images show a double nucleus and a 30 kpcmergers for which there is some detailed structural information. Deep optical Hubble
Space Telescope images show a double nucleus and a 30 kpc-size pair of continuum-
emitting 'tails' suggestive of a tidal origin, while i Space Telescope images show a double nucleus and a 30 kpc-size pair of continuum-
emitting 'tails' suggestive of a tidal origin, while infrared images show two emission-
line bubbles indicative of a strong bipolar wind (Ru emitting 'tails' suggestive of a tidal origin, while infrared images show two emission-
line bubbles indicative of a strong bipolar wind (Rush *et al.* 1997; McCarthy 1999).
Hence, at least some mergers at this high redsh line bubbles indicative of a strong bipolar wind (Rush *et al.* 1997; McCarthy 1999).
Hence, at least some mergers at this high redshift may have been similar to local
ones and involved pairs of already sizable discs.
The Hence, at least some mergers at this high redshift may have been similar to local

ones and involved pairs of already sizable discs.
The important role played by interactions and mergers is also becoming apparent
in galaxy *clusters* of increasingly high redshifts. Despite a widely held prejudice that
me The important role played by interactions and mergers is also becoming apparent
in galaxy *clusters* of increasingly high redshifts. Despite a widely held prejudice that
mergers cannot happen in clusters because of high ga mergers cannot happen in clusters because of high galaxy-velocity dispersions, both *Phil. Trans. R. Soc. Lond.* A (2000)

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theory and observations show unmistakably that strong interactions and mergers do
occur there. In some local clusters ongoing interactions and mergers are obvious. In theory and observations show unmistakably that strong interactions and mergers do
occur there. In some local clusters ongoing interactions and mergers are obvious. In
Hercules at least five major interactions and mergers a occur there. In some local clusters ongoing interactions and mergers are obvious. In Hercules at least five major interactions and mergers are visible in the central region alone (figure 5), and even in relaxed-looking Coma 'The Mice' (NGC 4676) provide an

example of a major merger occurring on the outskirts. In $z \approx 0.2$ –0.5 clusters a fair fraction of the blue galaxies causing the Butcher–Oemler effect (Butcher & Oemler 1978, 1984) have been found to be interacting or mer fraction of the blue galaxies causing the Butcher-Oemler effect (Butcher $\&$ Oemler while a majority appear to be disturbed gas-rich discs shaken either by high-velocity encounters or minor mergers (Dressler $et al.$ 1994; Barger $et al.$ 1996; Oemler $et al.$ 1978, 1984) have been found to be interacting or merging (Lavery & Henry 1994), while a majority appear to be disturbed gas-rich discs shaken either by high-velocity encounters or minor mergers (Dressler *et al.* 1994; Ba encounters or minor mergers (Dressler *et al.* 1994; Barger *et al.* 1996; Oemler *et al.* 1997). Most impressive are new Hubble Space Telescope images of the rich cluster MS 1054-03 at $z = 0.83$. Fully 17% of its 81 spec 1997). Most impressive are new Hubble Space Telescope images of the rich cluster MS 1054-03 at $z = 0.83$. Fully 17% of its 81 spectroscopically confirmed members are ongoing mergers, all with luminosities similar to, or h MS 1054-03 at $z = 0.83$. Fully 17% of its 81 spectroscopically confirmed members are ongoing mergers, all with luminosities similar to, or higher than, that of a L^* galaxy (van Dokkum *et al.* 1999). These mergers occu are ongoing mergers, all with luminosities similar to, or higher than, that of a L^* galaxy (van Dokkum *et al.* 1999). These mergers occur preferentially in the cluster outskirts, probably in small infalling clumps, an galaxy (van Dokkum *et al.* 1999). These mergers occur preferentially in the outskirts, probably in small infalling clumps, and present 'direct evidence the formation of ellipticals in a single monolithic collapse at high outskirts, probably in small infalling clumps, and present 'direct evidence against
the formation of ellipticals in a single monolithic collapse at high redshift'.
In order to quantitatively assess the impact of mergers on

In order to quantitatively assess the impact of mergers on galaxy evolution, one needs to determine the merger rate (i.e. the number of mergers per unit time and comoving unit volume) as a function of redshift. We can onl needs to determine the merger rate (i.e. the number of mergers per unit time and meeds to determine the merger rate (i.e. the number of mergers per unit time and
comoving unit volume) as a function of redshift. We can only hope to do this for
major mergers, since minor mergers are undetectable at $z \g$ comoving unit volume) as a function of redshift. We can only hope to do this for
major mergers, since minor mergers are undetectable at $z \gtrsim 0.5$ and accretions are
known only in the Local Group. There are many estimate č major mergers, since minor mergers are undetectable at $z \gtrsim 0.5$ and accretions are
known only in the Local Group. There are many estimates of the merger rate based on
counts of binary galaxies as a function of redshift known only in the Local Group. There are many estimates of the merger rate based on counts of binary galaxies as a function of redshift, and on the assumption that most such binaries will merge in a short time. This assump counts of binary galaxies as a function of redshift, and on the assumption that most
such binaries will merge in a short time. This assumption is a bit unrealistic, given
that even for a much-studied interacting pair like such binaries will merge in a short time. This assumption is a bit unrealistic, given
that even for a much-studied interacting pair like M 51 we do not know whether the
presumed merger will occur within 2, 5, or 10 Gyr. Ne that even for a much-studied interacting pair like M 51 we do not know whether the
presumed merger will occur within 2, 5, or 10 Gyr. Nevertheless, taken at face value
several recent estimates based on binary counts sugge presumed merger will occur within 2, 5, or 10 Gyr. Nevertheless, taken at face value
several recent estimates based on binary counts suggest a merger rate approximately
proportional to $(1 + z)^{3\pm 1}$ (see, for example, Ab several recent estimates based on binary counts suggest a merger rate approximat
proportional to $(1 + z)^{3\pm 1}$ (see, for example, Abraham *et al.* 1999), implying
order-of-magnitude increase in mergers at $z \approx 1$ compare

oportional to $(1 + z)^{3 \pm 1}$ (see, for example, Abraham *et al.* 1999), implying an
der-of-magnitude increase in mergers at $z \approx 1$ compared with the local rate.
Two estimates of numbers of mergers are relatively reliable order-of-magnitude increase in mergers at $z \approx 1$ compared with the local rate.
Two estimates of numbers of mergers are relatively reliable and bracket the range
of likely rates. First, given that there are around 11 ongo Two estimates of numbers of mergers are relatively reliable and bracket the range
of likely rates. First, given that there are around 11 ongoing disc mergers among
the 4000+ galaxies of the New General Catalog (NGC) and t of likely rates. First, given that there are around 11 ongoing disc mergers among
the $4000+$ galaxies of the New General Catalog (NGC) and their median 'age' is
ca. 0.5 Gyr, there should be about 250 remnants of similar the 4000+ galaxies of the New General Catalog (NGC) and their median 'age' is *ca*. 0.5 Gyr, there should be about 250 remnants of similar mergers among NGC galaxies *if* the rate has remained constant since high redshift ca. 0.5 Gyr, there should be about 250 remnants of similar mergers among NGC galaxies *if* the rate has remained constant since high redshifts, and about 750 remnants if, more realistically, the rate declined with time li galaxies *if* the rate has remained constant since high redshifts, and about 750 remnants if, more realistically, the rate declined with time like $t^{-5/3}$ (Toomre 1977).
Thus, nearly 20% of all NGC galaxies may be remnan

nants if, more realistically, the rate declined with time like $t^{-5/3}$ (Toomre 1977).
Thus, nearly 20% of all NGC galaxies may be remnants of major mergers, a fraction
that agrees remarkably well with the observed number Thus, nearly 20% of all NGC galaxies may be remnants of major mergers, a fraction
that agrees remarkably well with the observed number of elliptical and S0 galaxies.
Second, if all gas collapsed into discs and all spheroi that agrees remarkably well with the observed number of elliptical and S0 galaxies.
Second, if all gas collapsed into discs and all spheroids are due to mergers, then
the fractional amount of mass in spheroids—*ca*. 50% wh Second, if all gas collapsed into discs and all spheroids are due to mergers, then
the fractional amount of mass in spheroids—*ca*. 50% when estimated from bulge-to-
disc ratios of a complete sample of nearby galaxies—pro the fractional amount of mass in spheroids—*ca*. 50% when estimated from bulge-to-
disc ratios of a complete sample of nearby galaxies—provides an upper limit to the
integrated effect of all mergers (Schechter & Dressler disc ratios of a complete sample of nearby galaxies—provides an upper limit to the
integrated effect of all mergers (Schechter & Dressler 1987). This upper limit empha-
sizes that at least major mergers cannot have been t integrated effect of all mergers (Schechter & Dressler 1987). This upper limit emphasizes that at least major mergers cannot have been too frequent, or else they would have destroyed all discs. Especially in late-type, ne Gizes that at least major mergers cannot have been too frequent, or else they would
Chave destroyed all discs. Especially in late-type, nearly pure-disc galaxies (e.g. M 33
and M 101), most of the assembly must have been have destroyed all discs. Especially in late-type, nearly pure-disc galaxies (e.g. M33

6. Conclusions

6. Conclusions
This review has highlighted the role that interactions and mergers play in driving
galaxy evolution. At present we remain challenged to understand the relative impor-This review has highlighted the role that interactions and mergers play in driving galaxy evolution. At present we remain challenged to understand the relative impor-*Phil. Trans. R. Soc. Lond.* A (2000)

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tance of weak and strong interactions, the details of bulge formation, the existence tance of weak and strong interactions, the details of bulge formation, the existence
of nearly pure-disc galaxies, and the merger rate as a function of redshift. Yet, some
firm conclusions have been reached and are as foll tance of weak and strong interactions, the details of bul
of nearly pure-disc galaxies, and the merger rate as a fur
firm conclusions have been reached and are as follows.

- 1. Gravitational interactions and mergers are forming and transforming galaxies
throughout the observable Universe. The vast majority involve gas, dissination. Gravitational interactions and mergers are forming and transforming galaxies
throughout the observable Universe. The vast majority involve gas, dissipation,
and enhanced star formation. throughout the observable Universe. The vast majority involve gas, dissipation, and enhanced star formation.
- 2. The close link between mergers, ultra-luminous infrared galaxies, and quasars suggests that—like quasar activity—major merging may have peaked around $z \approx 2$.
- $z \approx 2$.
3. Major disc-disc mergers form elliptical galaxies with kinematic subsystems, bimodal globular-cluster populations, and remnant fine structure. Such mergers Major disc–disc mergers form elliptical galaxies with kinematic subsystems,
bimodal globular-cluster populations, and remnant fine structure. Such mergers
occurred relatively early near the centres of rich clusters, but co bimodal globular-cluster populations, and remnant fine structure. Such mergers occurred relatively early near the centres of rich clusters, but continue to the present time in rich-cluster outskirts, poorer clusters, and the field.
- 4. Minor mergers tend to move disc galaxies towards earlier morphological types, creating kinematic subsystems and some bulges (fraction remains unknown).
- The creating kinematic subsystems and some bulges (fraction remains unknown).

5. In short, the currently available evidence strongly suggests that Hubble's mor-

phological sequence is mainly a sequence of decreasing merg In short, the currently available evidence strongly suggests that Hubble's phological sequence is mainly a sequence of decreasing merger damage.

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