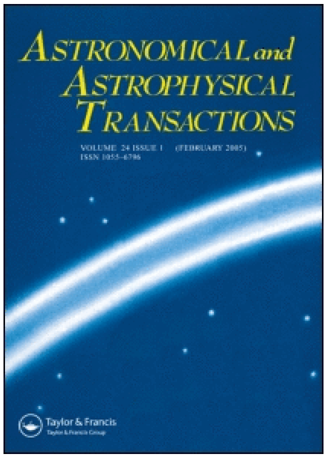

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LARGE-SCALE RING WAVES OF STAR FORMATION IN THE CARTWHEEL RING GALAXY

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Numerical modelling of propagating ring waves of star formation initiated by an off-center head-on galactic collision is performed. It is demonstrated that the observed azimuthal Hα surface brightness profile of the Cartwheel's outer ring can be approximately reproduced for a moderate off-center collision, with the impact point 3–4 kpc displaced from the dynamical center. For larger impact points the ring wave of star formation breaks into a spiral, which cannot account for the observed morphology of the Cartwheel ring galaxy.

Keywords: Galaxies: individual: the Cartwheel – Galaxies: photometry – Galaxies

1 INTRODUCTION

The Cartwheel galaxy is an archetype ring galaxy possessing a number of remarkable properties. Among them are the Hα observations (Higdon, 1995), which indicate that almost all star formation is localised within the Cartwheel's outer ring located at the distance of 16 kpc from the nucleus ($H = 100\,\mathrm{km\,s^{-1}\,Mpc^{-1}}$). The H$\alpha$ kinematics and spectroscopic studies show that the outer ring is expanding with the velocity of 50–90 $\mathrm{km\,s^{-1}}$ (Higdon, 1996; Fosbury and Hawarden, 1977). Finally, the Cartwheel's disk has the B-V/V-K radial color gradients, with the inner parts of the disk being redder than the outer parts (Marcum *et al.*, 1992). This observational evidence implies the presence of an expanding ring wave of star formation in the Cartwheel's disk. The luminous outer ring is probably a current location of such a wave (Marcum *et al.*, 1992).

In the series of papers by Korchagin and co-authors (1995; 1998; 2001) a theoretical model, describing the processes of propagation of ring waves of star formation in ring galaxies, has been developed. According to this model, an axial collision of a target galaxy with one of its companions triggers a burst of star formation in the nuclear regions of the target galaxy. The burst of star formation serves as an initial trigger, which initiates an expanding ring wave of star formation in the gas-rich galactic disk of the target galaxy. As such a ring wave advances outwards, it burns the gas supply, leaving in its wake evolved stellar populations. This makes the model conceptually similar to the "fire in the forest"

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(FIF) model of Seiden and Gerola (1982). As to the Cartwheel galaxy, this scenario seems possible. The gas plume stretching from the Cartwheel to one of its companions serves as an indicator of such a collision in the Cartwheel's recent past (Higdon, 1996). The Cartwheel is gas-rich, with the neutral hydrogen mass of $\approx 2 \times 10^{10}\,M_\odot$ (Mebold *et al.*, 1977).

Using the FIF model Korchagin *et al.* (1998; 2001) successfully modelled the Cartwheel's radial surface brightness profiles in Hα and R-band, as well as the radial B-V/B-K color gradients. This modelling though was strictly one-dimensional when the ring wave of star formation propagated exactly from the dynamical center of the galaxy, thus implying an axial bull-eye collision. However, the Cartwheel galaxy has a few remarkable properties, which cannot be accounted for in an exact central collision. Azimuthal variations in Hα surface brightness detected around the Cartwheel's outer ring and the nucleus displaced with respect to the geometrical center of the outer ring favour the off-center collision of the Cartwheel galaxy with one of its companions.

In this paper we perform a two-dimensional modelling of propagating ring waves of star formation in the Cartwheel galaxy initiated by off-center collisions. We show that the FIF model can reproduce the azimuthal variation in Hα surface brightness around the outer ring, if the impact point is 3–4 kpc displaced from the dynamical center. In Section 2 the basics of the FIF model are presented. In Section 3 the main results are discussed. Conclusions are made in Section 4.

2 THE "FIRE IN THE FOREST" MODEL

Propagation of star formation at small scales comes when one considers the non-linear influence of massive stars on the interstellar medium. Supernova shock waves, ionised shells around young massive stars, implosion by ultraviolet radiation, and other massive-star-involved processes might trigger further star formation in nearby gas complexes on scales less than 1–2 kpc. To model the expanding ring wave of star formation in the Cartwheel galaxy, we use the FIF model (Korchagin *et al.*, 1995; 1998) describing the processes of propagation of star formation in a stellar-gaseous medium. In the FIF model the propagation of star formation in a gaseous disk of surface density Σ_g is governed by the following set of mass balance equations:

$$\frac{\mathrm{d}\Sigma_s}{\mathrm{d}t} = -D + ka\Sigma_g(\mathbf{r}, t - T)\int_{\mathbf{r}' \le L} \mathrm{d}\mathbf{r}' f(\mathbf{r} - \mathbf{r}')\Sigma_s(\mathbf{r}', t - T), \tag{1}$$

$$\frac{\mathrm{d}\Sigma_g}{\mathrm{d}t} = -a\Sigma_g(\mathbf{r}, t)\int_{\mathbf{r}' \le L} \mathrm{d}\mathbf{r}' f(\mathbf{r} - \mathbf{r}')\Sigma_s(\mathbf{r}', t). \tag{2}$$

Equation (1) accounts for the decrease of surface density of gas due to star formation. Equation (2) is the balance of surface density of stars Σ_s, with the second term in the right-hand side accounting for the increase of Σ_s due to massive-star-induced star formation. The function $f(\mathbf{r} - \mathbf{r}')$ represents the non-local nature of induced star formation, which only takes place within the radius of influence L. Time delay T is the time that takes for the young association of massive stars to trigger star formation in the nearby gaseous complexes. Presence of fainter star-forming regions in advance of the Cartwheel's outer ring and their close association with luminous ring HII regions (Hα bridges are present in some cases) implies that they have been spawned by shocks or stellar winds breaking out from the outer ring (Higdon, 1995). This allows us to choose 1 kpc and 10 Myr as characteristic values for the radius of influence L and time delay T respectively. The ratio L/T determines the propagation velocity of star formation. The efficiency of star formation is chosen as $k = 0.1$. The death rate of stars D is defined so as to give the detailed information on the mass and age spectra of stellar populations formed in the wave of star formation:

$$D = \frac{ka}{\sum_{m_1}^{m_2} m^{1-\alpha}} \sum_{m_1}^{m_2} m^{1-\alpha} \Sigma_g(\mathbf{r}, t - T - \tau_m) \int_{\mathbf{r}' \leq L} \mathrm{d}\mathbf{r}' f(\mathbf{r} - \mathbf{r}') \Sigma_s(\mathbf{r}', t - T - \tau_m), \tag{3}$$

with the Salpeter slope of the initial mass function $\alpha = 2.35$ and the lower and upper mass limits being $m_1 = 0.1\,\mathrm{M}_\odot$ and $m_2 = 100\,\mathrm{M}_\odot$ respectively.

Equations (1)–(3) were solved numerically in the polar coordinates. As the initial conditions we suppose that the off-center collision initiates in the vicinity of the impact point a burst of star formation, which later on develops into a ring wave of star formation in the gas-rich disk of the Cartwheel galaxy. Thus, $\Sigma_s(r, t = 0) \neq 0$ in the $r \leq 1\,\mathrm{kpc}$ radius and $\Sigma_s(r, t = 0) = 0$ in the other parts of the disk. We numerically traced the propagation of star formation wave on 100×100 computational mesh from the impact point to the radius of 16 kpc, which is the current location of the Cartwheel's outer ring. We assume that initially the Cartwheel has an exponential surface density profile of gas:

$$\Sigma_g(r, t = 0) = A \exp\left(\frac{-r}{h}\right), \tag{4}$$

where the central surface density of gas $A = 50\,\mathrm{M}_\odot\,\mathrm{pc}^{-2}$ and the scale length $h = 11\,\mathrm{kpc}$ are chosen so as to reproduce the Hα and R-band surface brightness profiles of the Cartwheel (Korchagin *et al.*, 2001). The stellar populations existed in the Cartwheel's disk before the collision are accounted for in the manner described in Korchagin *et al.* (2001).

Specific choice of the stellar death rate (Eq. (3)) allows one to find the stellar mass and age spectra in each computational grid and thus to apply a population synthesis code for deriving the photometric properties of stellar populations formed in the star formation wave. The population synthesis code used in this work is explained in detail in Mayya (1995; 1997). This code synthesises a number of observable quantities in the optical and near-infrared parts of the spectrum, which are suitable for comparison with the observed properties of giant star-forming complexes. Since the Cartwheel is a recent phenomenon with high rates of star formation, this code is especially suitable for our purposes. The results of this code are compared with those of other existing codes by Charlot (1996). Use of this code in two-dimensional computations is however confronted with considerable difficulties. Modelling of radial surface brightness profiles of the Cartwheel galaxy has shown that the mass and age discretisation in the code should be as small as $\Delta m = 0.1\,\mathrm{M}_\odot$ and $\Delta t = 0.2\,\mathrm{Myr}$ respectively to achieve the desired accuracy (Korchagin *et al.*, 2001). With such a small discretisation, the number of massive stars with mass m and age t in each radial annulus on the one-dimensional mesh amounts to no more than a few. In case of the two-dimensional mesh the radial annulus splits into tens of sectors depending on the angular discretisation, which lowers the number of massive stars in each sector accordingly. This results in an artificial cut-off of the upper mass limit of the IMF. Since the Hα flux is dominated by massive stars ($m > 10\,\mathrm{M}_\odot$), this would underestimate the value of Hα surface brightness.

To model the Hα surface brightness, we utilize the well-known relationship between Hα luminosity and the star formation rate (SFR):

$$\mathrm{SFR}\ (\mathrm{M}_\odot\,\mathrm{yr}^{-1}) = \mathit{factor} \times L_{H\alpha}(\mathrm{ergs\,s}^{-1}). \tag{5}$$

Kennicatt *et al.* (1994) gave several conversion factors between the Hα luminosity and the SFR according to the IMF, metallicity, and stellar evolutionary models used in their work. These conversion factors were derived using a constant star formation model, which is a rude approximation for the ring galaxies such as the Cartwheel (Korchagin *et al.*, 2001). Moreover, they adopted the solar metallicity, which is most probably not the case for the Cartwheel's outer ring.

To constrain the optimal value of conversion factor, we perform the one-dimensional modelling of the Hα radial surface brightness profile observed in the Cartwheel's disk employing both the population synthesis code as it was done in Korchagin *et al.* (2001) and the relationship given by Eq. (5). Best agreement between the Hα radial profiles obtained by these two different methods and observed Hα radial profile is achieved for $factor = 5.8 \times 10^{-42}$, the value reported by Kennicutt *et al.* (1994) for the Salpeter IMF, solar metallicity, and the stellar evolutionary model of Maeder and Meynet (1989). Hence, we use this value of conversion factor in our work. The model R-band surface brightness in two-dimensional calculations is obtained using population synthesis, as the R-band flux is dominated by intermediate and lower mass stars ($m < 10\,M_{\odot}$), the number of which in each two-dimensional zone is much more than unity.

The FIF model confronts an obvious difficulty as far as the propagation of star formation waves in ring galaxies is concerned. Differential rotation tends to transform any coordinated ring wave of star formation into a spiral, unless it advances exactly from the dynamical center of a ring galaxy. On the other hand, ring galaxies are young phenomena. The age of the Cartwheel galaxy is about 250–300 Myr as estimated by Higdon (1996), which is comparable to the galactic revolution period. One can expect that on such a small time scale the ring wave of star formation triggered by a moderate off-center collision might preserve its ring shape. Indeed, development of ring structures on 10 kpc scales has been reported by Seiden *et al.* (1982) in their stochastic self-propagated star formation model.

3 RESULTS

In this section the results of two-dimensional modelling of propagating ring waves of star formation initiated by an off-center head-on collision of the Cartwheel galaxy with an intruder galaxy are presented. The impact point varies from $r = 1$ kpc to $r = 6$ kpc, where r is the radial distance from the dynamical center of the model gaseous disk (Eq. (4)). The rotation curve is taken from Higdon (1996). Abundance measurements in the Cartwheel's outer ring indicate that the oxygen, nitrogen, and neon are deficient by factors of 6 ± 2, 22 ± 4, and 3 ± 2 respectively. The metallicity of the star-forming gas is thus chosen as $z_{\odot}/5$. Velocity of radial propagation of star formation wave is fixed at $90\,\mathrm{km\,s^{-1}}$ (Marcum *et al.*, 1992; Korchagin *et al.*, 1998).

Simulations show that the Hα azimuthal profile in the Cartwheel's outer ring can be approximately reproduced for a moderate off-center collision at $r = 4$ kpc. This value of the impact point has lower and upper limits. For large r the agreement between the model and the Cartwheel's Hα azimuthal profiles of the outer ring improves, while the wave of star formation loses its ring shape transforming into a spiral. For smaller r the model Hα azimuthal profile becomes progressively axisymmetric. The solid lines in Figures 1a and lb show the model Hα and R-band azimuthal profiles in the Cartwheel's outer ring obtained for the impact point located at $r = 4$ kpc from the dynamical center. The filled triangles represent the observed azimuthal profiles in the Cartwheel's outer ring as measured by Higdon (1995; 1996). The model Hα profile approximately fits the Cartwheel's one, though

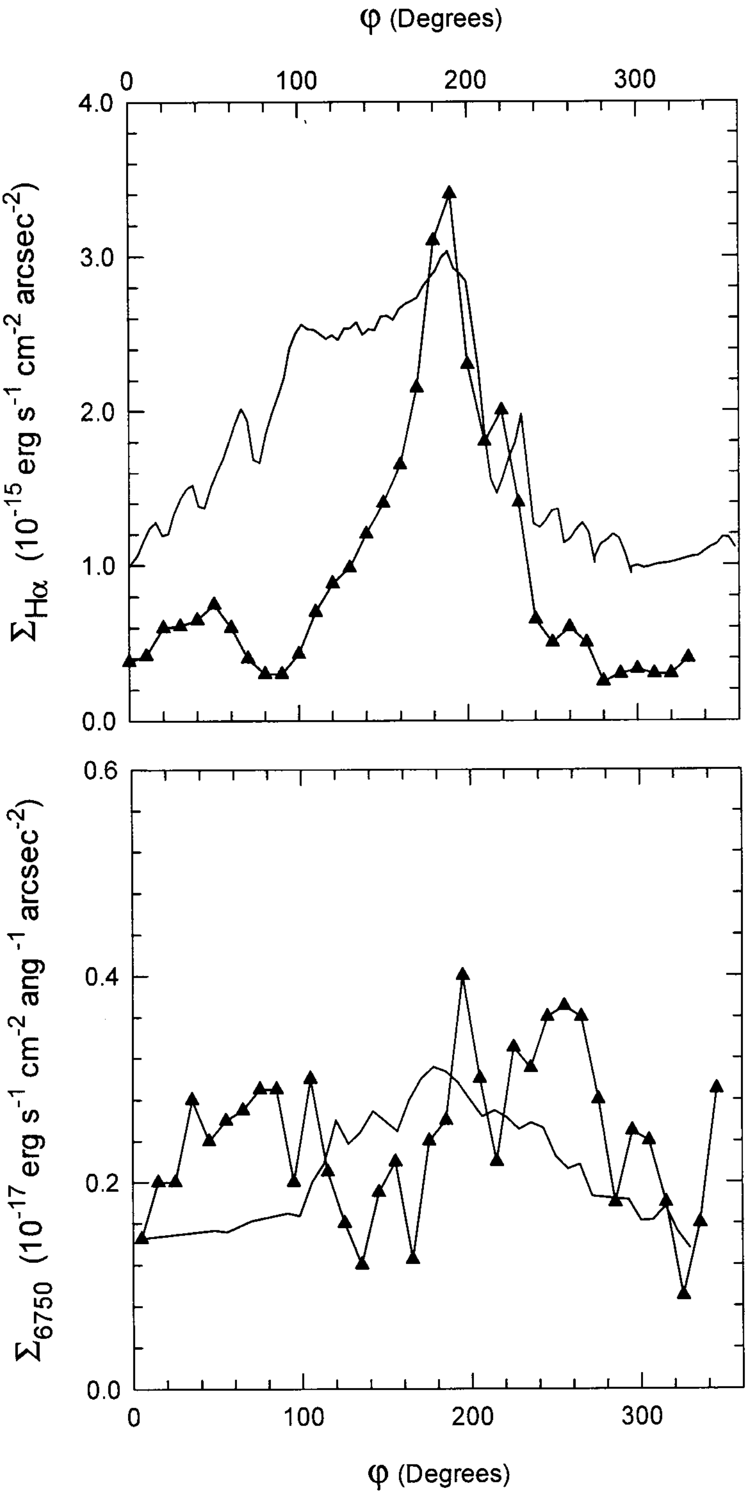

FIGURE 1 The model (solid lines) and the observed (filled triangles) azimuthal $H\alpha$ and R-band surface brightness profiles of the Cartwheel's outer ring.

overestimating the observed values everywhere except for the position angles at 175°–240°. This is where two most luminous Hα knots of the outer ring are located – CW17 (185°) and CW24 (231°) (Higdon, 1995). The 175°–240° sector of the outer ring is the closest to the dynamical center and hence of the highest gas surface density. The sudden drop in Hα surface brightness in the other parts of the outer ring is likely to be the result of an overall reduction in gas density, possibly below a critical threshold for star formation – the effect not accounted for in the simple FIF model used in this work.

The R-band azimuthal profile in the Cartwheel's outer ring is reproduced in Figure lb only approximately for the position angles at 200°–330°, where the overall decline of the observed R-band surface brightness in the direction of increasing angle is evident. The precollision stellar populations contribute significantly to the R-band flux emitted from the outer ring, contrary to the Hα flux that is dominated by wave-born post-collision stellar populations (Korchagin *et al.*, 2001). The complicated azimuthal distribution of R-band surface brightness around the outer ring is likely to be the result of non-axisymmetric distribution of pre-collision stellar populations in the Cartwheel, which most probably was a normal spiral before the collision (Korchagin *et al.*, 2001).

In Figure 2 the model contour plot of Hα surface brightness is superimposed on the Cartwheel's Hα map obtained by Higdon (1995). The inclination of the Cartwheel to the

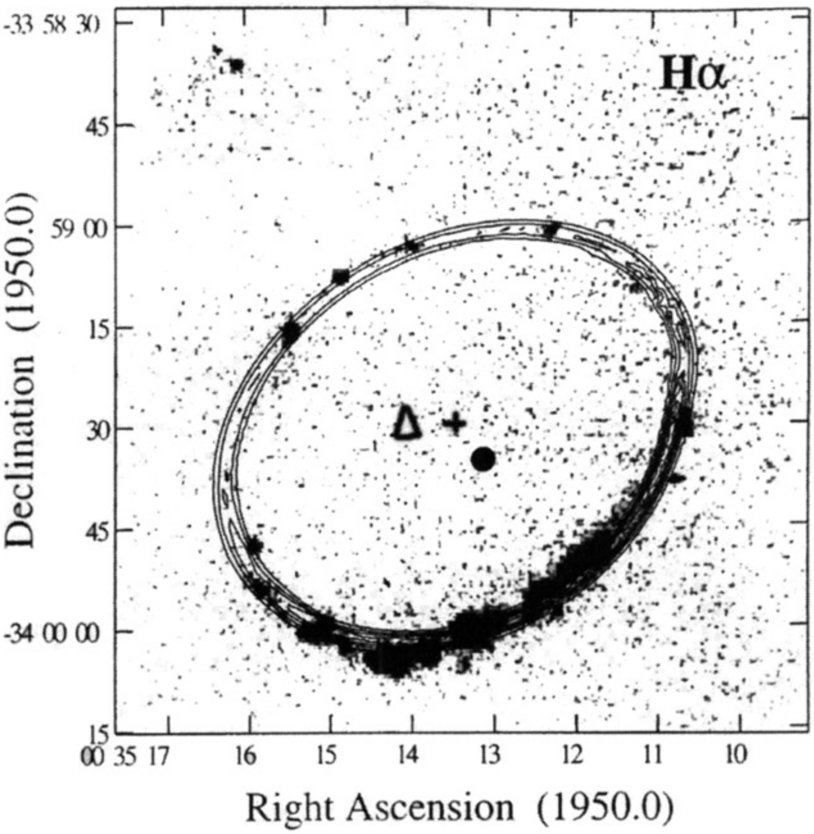

FIGURE 2 Superposition of the model Hα surface brightness contour plot and Hα map of the Cartwheel galaxy obtained by Higdon (1995). The open triangle marks the nucleus (not seen in Hα), while the filled circle and the cross mark the dynamical center of model gaseous disk (Eq. (4)) and the impact point respectively. The contour levels are 1, 2, 3, 4 in units 10^{-15} erg s^{-1} sm^{-2} arcsec^{-2}.

line of sight is taken into consideration. The dynamical center of *the model gaseous disk* is marked by the filled circle, whereas the impact point is labelled by the cross. The dynamical center of the model gaseous disk is displaced with respect to the geometrical center of the Cartwheel's outer ring. The location of *the true dynamical center* of the Cartwheel is not clearly determined from observations and the question whether the filled circle in Figure 2 coincides with the true geometrical center of the Cartwheel or not is still open. However, there is a hint that the dynamical and geometrical centers of the Cartwheel do not coincide. The rotational curves (RC) of the approaching and receding sides of the Cartwheel measured from the Hα kinematics significantly differ from each other (Amram *et al.*, 1998). Specifically, the rotation velocities of the approaching side (right-hand side in Fig. 2) are systematically below the rotation velocities of the receding side (left-hand side in Fig. 2). The measurements are performed under an assumption that the center of the RC coincides with the geometrical center of the outer ring. For circular orbital motions of gas in the Cartwheel, this difference of approaching and receding RCs might imply the displacement of the dynamical center of the Cartwheel to the right with respect to the geometrical center of the outer ring, the feature predicted by our simulations.

The displacement of the Cartwheel's nucleus with respect to the geometrical center of the outer ring is also noteworthy. Since the impact point is located approximately midway between the nucleus marked with the open triangle in Figure 2 and the dynamical center marked with the filled circle in Figure 2, the displacement of the nucleus is likely to be due to the gravitational drag of a companion galaxy exerted on the Cartwheel's nucleus during the collision. More sophisticated models of ring galaxy formation are needed to clarify this point.

4 CONCLUSIONS

In this paper the two-dimensional modelling of propagating ring waves of star formation in the Cartwheel galaxy is performed with a view to reproduce the observed azimuthal Hα and R-band surface brightness profiles of the Cartwheel's outer ring. The "Fire in the Forest" model is used when the off-center head-on collision of the Cartwheel with one of its companions triggers an initial burst of star formation around the impact point. The burst then develops into a self-propagating ring wave of star formation, which leaves behind evolved stellar populations on its way to the outermost radii (Korchagin *et al.*, 1995; 1998).

Numerical modelling shows that the large variations in the azimuthal Hα surface brightness profile of the Cartwheel's outer ring can be reproduced to some extent in a moderate off-center collision, with the impact point 3–4 kpc displaced from the dynamical center. For larger impact points the ring wave of star formation breaks into a spiral, which can not account for the observed morphology of the Cartwheel ring galaxy. For smaller values of the impact point the model azimuthal profile in Hα becomes progressively axisymmetric. The azimuthal R-band surface brightness profile of the outer ring is difficult to model, which is likely to be due to a complicated influence of pre-collision stellar populations extending out in the Cartwheel's disk to the current position of the outer ring. The location of the Cartwheel's nucleus approximately in a line stretching from the model dynamical center to the impact point implies that the nucleus might have been displaced as a result of recent galactic collision.

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